AN INVESTIGATION OF THE INTAKE PIPE ORIFICE

A THESIS

PRESENTED TO THE MECHANICAL ENGINEERING DEPARTMENT

OF THE GEORGIA SCHOOL OF TECHNOLOGY IN PARTIAL

FULFILLMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

BY

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MAY, 1934

APPROVED BY

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ACKNOWLEDGEMENTS

THE AUTHOR TAKES THIS MEANS OF EXPRESSING HIS APPRECIATION TO PROFESSOR N. C. EBAUGH WHO SUGGESTED THE RESEARCH AND FURNISHED MANY HELPFUL SUGGESTIONS, AND WHOSE PRACTICAL ADVICE FACILITATED ITS ACCOMPLISHMENT. ALSO THE AUTHOR WISHES TO THANK MR. WILLIS D. LUDWIG AND MR. GEORGE VAN SCHLIESTETT WHO AIDED IN THE CALIBRATION OF SOME OF THE INSTRUMENTS.

I. NATURE OF THE INVESTIGATION

A. AIMS

THIS INVESTIGATION OF THE THIN PLATE PLATE ORIFICE FOR METERING AIR WHEN LOCATED ON THE INTAKE END OF A PIPE WAS MADE WITH TWO MAIN OBJECTS IN VIEW:

1. TO DETERMINE THE FEASIBILITY OF THIS TYPE OF FLOW MEASUREMENT.
   (A) LOCATION OF THE VENA CONTRACTA FOR ORIFICE SIZES FROM 20% TO 100% OF THE PIPE AREA AND FOR PRESSURE DIFFERENTIALS FROM 2.3 TO .051 INCHES OF WATER.
   (B) DETERMINATION OF THE COEFFICIENT OF DISCHARGE FOR VARIOUS ORIFICE SIZES AND DIFFERENTIAL PRESSURES.
   (C) FINDING THE EFFECT OF IMPROPERLY MADE ORIFICE PLATES ON THE COEFFICIENT OF DISCHARGE.

2. TO DETERMINE WHETHER OR NOT AIR FLOW MAY BE ACCURATELY METERED BY AN ORIFICE AT VERY SLIGHT PRESSURE DIFFERENTIALS. THE TEST INCLUDES ORIFICE DIFFERENTIALS AS LOW AS .051 INCHES OF WATER AND VELOCITIES IN THE DUCT AS LOW AS ABOUT 5 FEET PER SECOND.

B. APPLICATIONS

ASIDE FROM THE PURELY SCIENTIFIC VALUE OF INVESTIGATING THE CHARACTERISTICS OF THE FLOW THROUGH THIS TYPE OF ORIFICE, SUCH AS THE COEFFICIENT OF DISCHARGE, THE LOCATION OF THE VENA CONTRACTA, AND WHETHER OR NOT THIS LOCATION SHIFTS WITH THE PRESSURE DIFFERENTIAL, ETC., THERE ARE SOME PRACTICAL ADVANTAGES IN ITS USE ALREADY APPARENT:

1. IT MAY BE USED AS A MUCH SIMPLIFIED METHOD OF TESTING PROPELLER FANS, BLOWERS, AND EXHAUST FANS.

2. IT MAY BE USED ON ANY TYPE OF AIR INTAKE, SUCH AS FOUND IN HEATING, VENTILATING, AND AIR CONDITIONING WORK, AND IS ESPECIALLY ADVANTAGEOUS WHERE IT WOULD BE INCONVENIENT TO BREAK INTO A DUCT TO INSERT A PIPE ORIFICE.

3. IT IS ADAPTABLE TO CONFINED SPACES WHERE IT WOULD BE IMPOSSIBLE TO USE A VENTURIMETER, PIPE ORIFICE, OR PITOT TRAVERSE, SINCE ALL OF THE LATTER REQUIRE A LONG UNIFORM APPROACH SECTION.

4. IT IS SIMPLE TO CONSTRUCT AND REQUIRES NO ACCURATE MACHINING. IN LARGE SIZES THE ORIFICES MAY BE CUT WITH A COLD CHISEL.

5. ONLY ONE PRESSURE TAP AND CONNECTION IS NEEDED.

6. NO VELOCITY OF APPROACH FACTOR NEED BE CALCULATED.

7. ONE COEFFICEENT OF DISCHARGE MAY BE USED FOR ORIFICE SIZES FROM 20 TO 100% POPE AREA AND FOR PRESSURE DIFFERENTIALS FROM 1 TO 2 INCHES OF WATER AND BE WITHIN ABOUT 1% ERROR.

C. Previous Work

After a search of the Transactions of the American Society of Mechanical Engineers, The Engineering Index, and other sources of engineering information, No previous work has been found dealing with an orifice located on the end of an intake pipe. Neither has any record been found of work dealing with as small pressure differentials for orifices as are used in this investigation. The lower limits of practically all orifice work has been about one inch of water pressure, with the exception of a few instances, mostly in Europe, where the range of investigation extended below this value.

The nearest approach to this type orifice is perhaps the metering device developed by R. J. Durley[1], and further investigated in modified forms by J. A. Polson[2] in this country, and Muller[3] in Germany. However, these experiments differ from the one discussed here, for in their case air was discharged into the atmosphere through an orifice from a relatively large reservoir, whereas in the intake pipe orifice air is drawn through an orifice plate directly from the atmosphere into a pipe. They are similar in that the orifice plate is not located in the pipe line as is customary, and that the approach velocity of air entering the orifice is negligible.

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1. R. J. Durley—On the Measurement of Air Flowing Through Circular Orifices Into the Atmosphere—ASME Transactions—1906

2. J. A. Polson-The Flow of Air Through Circular Orifices in Thin Plates-University of Illinois Bulletin #240 - 1932

3. E. Ower - Measurement of Air Flow-Chapman & Hall, Ltd., London-1933

Tests using the Durley Box type of orifice for the intake of air have been conducted by the National Advisory Committee for Aeronautics[1] in America and by Watson and Schofield [2] in England. However, in both cases the orifice sizes were below two inches and used in large reservoirs. Also, the lower limit of the differential pressures they used was one half inch of water compared to .051 inch used in this work.

Regarding locating the vena contracta, much work has been done in this field, but only for orifices in pipes, with the exception of the research by Professor R. S. King and Professor H. Judd[3]. They located and actually measured the size of the vena contracta of jets of water issuing into the air from a frictionless orifice. In pipe orifices, some notable work in locating the vena contracta has been done by J. M. Spitzglass[4], Horace Judd[5], and E. Buckingham[6].

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1. Ware-Effect of the Reversal of Air Flow Upon the Discharge Coefficient of Durley Orifices - Technical Notes, National Advisory Committee for Aeronautics - No. 40-1931

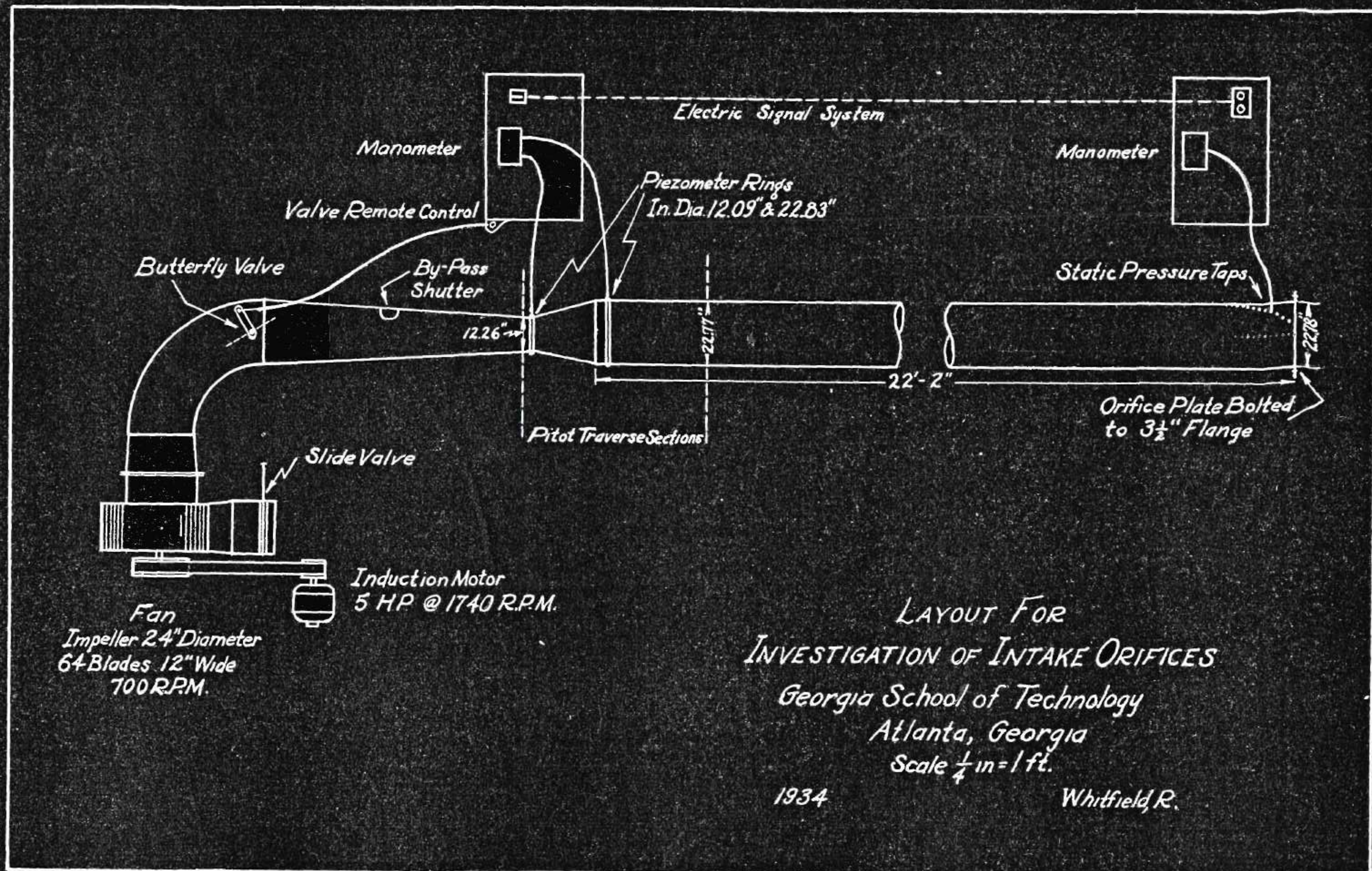
2. E. Ower-Measurement of Air Flow-Chapman & Hall, Ltd., London-1933

3. R. S. King and H. Judd-Some Experiments in the Frictionless Orifice - Engineering News, Vol. 56, pp. 326-330 - 1906

4. J. M. Spitzglass-Orifice Coefficients-ASME Transactions p. 919 - 1922

5. Horace Judd-Experiments on Water Flow Through Pipe Orifices ASME Transactions, p. 331 - 1916

6. E. Buckingham-H. S. Bean, M. E. Benesh-Experiments in Metering Large Volumes of Air - Bureau of Standards Research Paper No. 335 - 1931


Electric Signal System
Manometer
Manometer
Valve Remote Control
Piezometer Rings
In. Dia. 12.09" & 22.83"
Butterfly Valve
By-Pass
Shutter
Static Pressure Taps
12.26"
22.77"
22.78"
22'-2"
Orifice Plate Bolted
to 3½" Flange
Pitot Traverse Sections
Slide Valve
Induction Motor
5 HP @ 1740 R.P.M.
Fan
Impeller 24" Diameter
64 Blades 12" Wide
700 R.P.M.
LAYOUT FOR
INVESTIGATION OF INTAKE ORIFICES
Georgia School of Technology
Atlanta, Georgia
Scale ¼ in = 1 ft.
1934
Whitfield, R.

II. INSTRUMENTS AND EQUIPMENT

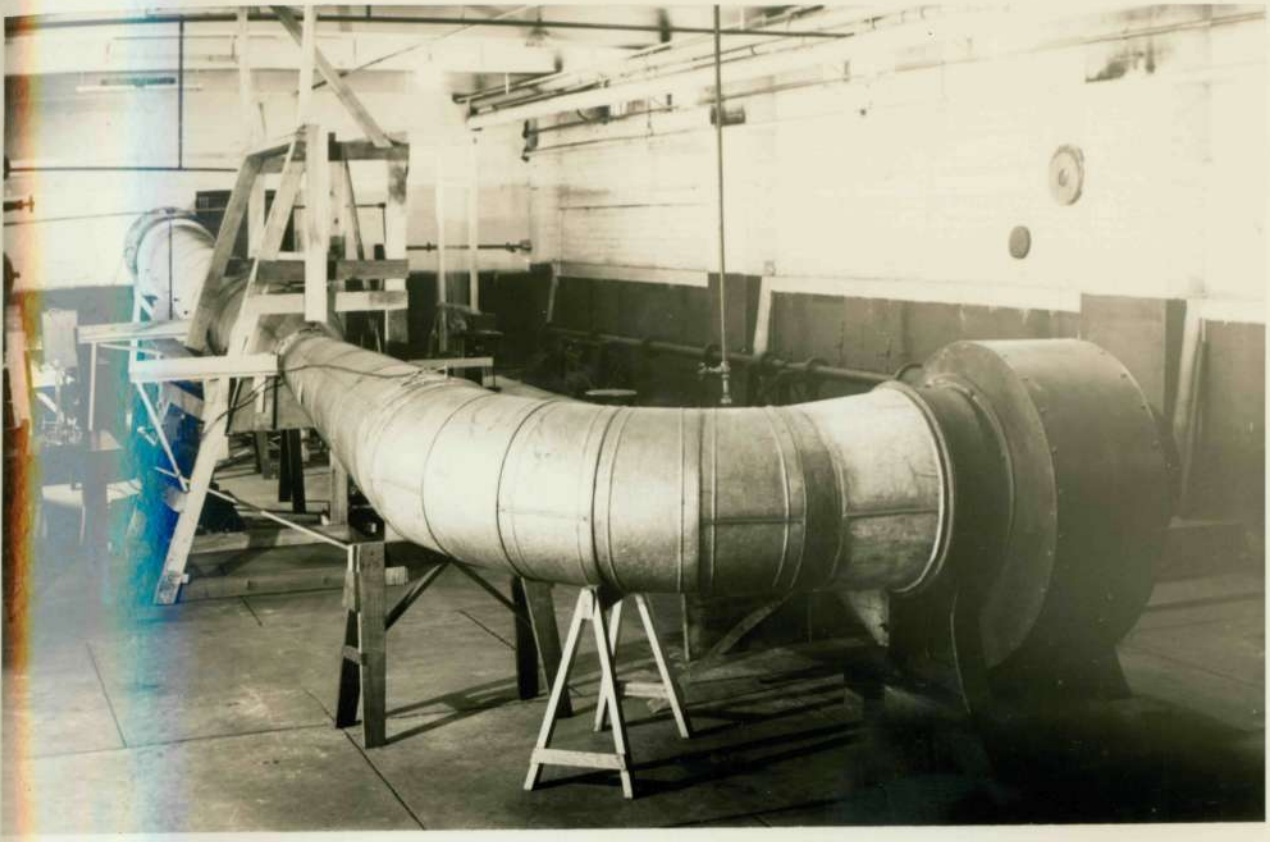
A. GENERAL LAYOUT

THE PLAN ON PAGE 5 DRAWN TO SCALE AND THE PHOTOGRAPH ON PAGE 7 SHOW THE ARRANGEMENT AND SIZE OF THE EQUIPMENT. IT WAS SET UP IN THE BASEMENT OF THE MECHANICAL ENGINEERING BUILDING OF THE GEORGIA SCHOOL OF TECHNOLOGY IN THE SPRING OF 1934. THE REFRIGERATION APPARATUS SEEN IN THE PHOTOGRAPH WAS BUILT FOR AN INVESTIGATION OF HEAT TRANSFER IN AIR COOLING UNITS, AND THE AIR FOR THIS TEST WAS TO HAVE BEEN SUPPLIED BY THE SAME FAN, BUT DURING THE TESTS DISCUSSED HERE THE FAN DISCHARGED DIRECTLY TO THE ATMOSPHERE. IT WAS ORIGINALLY PLANNED TO CHECK THE ACTUAL FLOW OF AIR BY HEAT BALANCES ON THE COOLING UNIT AND ON A STEAM HEATING RADIATOR ALSO IN THAT LINE, BUT THIS PLAN WAS ABANDONED.

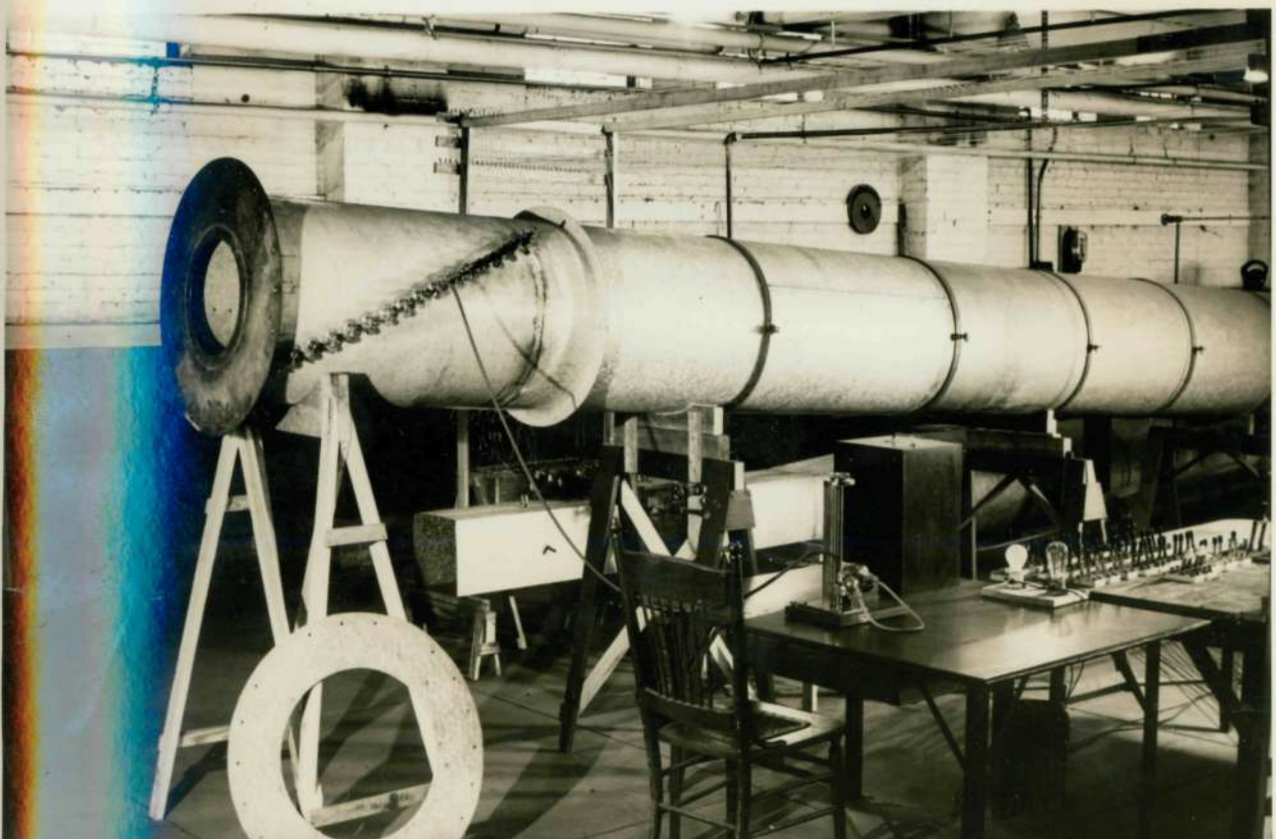
ALL MEASUREMENTS WERE MADE ON THE SUCTION SIDE OF THE FAN. REFERRING TO THE DIAGRAM, AIR ENTERS THE SYSTEM THROUGH THE INTAKE ORIFICE PLATE AND FLOWS THROUGH THE VENTURIMETER TO THE FAN INTAKE.

THE INTAKE PIPE ON WHICH THE ORIFICE PLATES WERE MOUNTED WAS INCLINED AT AN ANGLE OF FOUR DEGREES TO HAVE THE ORIFICE OPENING AWAY FROM ANY EFFECT OF THE PROXIMITY OF THE FLOOR AND TO AFFORD BETTER ACCESS TO THE REFRIGERATOR EQUIPMENT.

AS SEEN IN THE DIAGRAM THE MANOMETERS FOR THE ORIFICE AND FOR THE VENTURIMETER WERE EACH LOCATED AS NEAR AS POSSIBLE TO THEIR RESPECTIVE POINTS OF PRESSURE MEASUREMENT SO THAT THE CONNECTION LENGTHS WOULD BE A MINIMUM. THIS



GENERAL VIEW OF APPARATUS



THE INTAKE PIPE ORIFICE

REDUCES POSSIBLILITES OF LEAKS AND SHORTENS THE TIME LAG OF INDICATING VARIATIONS IN FLOW.

THIS ARRANGEMENT NECESSITATED A SIGNAL DEVICE SO THAT THE OPERATOR KEEPING THEFLOW THROUGH THE VENTURIMETER CONSTANT MAY INFORM THE OPERATOR AT THE ORIFICE METER IF THE FLOW IS CORRECT, TOO HIGH OR TOO LOW. THIS WAS ACCOMPLISHED BY SIGNAL LIGHTS OPERATED BY A KEY AT THE VENTURIMETER STATION.

THE WOODEN FRAME WORK SEEN MIDWAY OF THE PIPE LINE SUPPORTS THE PITOT TUBE TRAVERSE GUIDES.

B. THE FAN, MOTOR, AND DUCTWORK

THE FAN USED A SIROCCO #4 MULTIBLADE BLOWER, BUILT BY THE AMERICAN BLOWER CO. OF DETROIT. THE DIAMETER OF THE IMPELLER WAS 24 INCHES AND HAD 64 BLADES 10 INCHES WIDE. THE SCROLL CASING WAS 16 INCHES WIDE AND THE DIAMETER OF THE INTAKE WAS 25 INCHES., WHILE THE DISCHARGE WAS 20 INCHES SQUARE. IT WAS BELT DRIVEN AT 700 RPM BY A 220 VOLT 3 PHASE INDUCTION MOTOR DEVELOPING 5HP AT 1740 RPM.

THE DUCT WORK WAS OF 22 GAGE GALVANIZED IRON PIPE 22.75 INCHES INSIDE DIAMETER. ALL JOINTS WERE SOLDERED AIR TIGHT, AND ALL ROUGH PROJECTIONS ON THE INSIDE AT THE JOINTS WERE REMOVED. STEEL REINFORCING HOOPS WERE PLACED AROUND THE PIPE TO INSURE A ROUND CROSS SECTION AT ALL POINTS.

C. CONTROL OF FLOW

SINCE A CONSTANT SPEED INDUCTION MOTOR WAS USED TO DRIVE THE FAN, OTHER MEANS HAD TO BE PROVIDED TO REGULATE THE FLOW OF AIR. THIS WAS ACCOMPLISHED BY THREE METHODS:

(A) BY A SLIDING SHUTTER AT THE FAN DISCHARGE TO MAKE MAJOR CHANGES IN THE FLOW.

(B) BY A BUTTERFLY VALVE BETWEEN THE FAN AND VENTURIMETER TO MAKE FINE ADJUSTMENTS AND TO COMPENSATE FOR VARIATIONS IN THE VELOCITY DURING A RUN. A FLEXIBLE CABLE CONTROL PERMITTED THE OPERATOR SEATED AT THE VENTURIMETER MANOMETER TO MAINTAIN A GIVEN RATE OF FLOW BY WATCHING THE MANOMETER.

(C) BY BY-PASSING AIR TO THE FAN. AT VERY LOW VELOCITIES THE BUTTERFLY VALVE WAS FOUND INEFFECTUAL, AS IT WAS PURPOSELY MADE SMALLER THAN THE CROSS-SECTION OF THE PIPE TO PERMIT FINE ADJUSTMENTS AT HIGH SPEEDS. HENCE IT WAS NECESSARY TO BY-PASS AIR INTO THE DUCT AHEAD OF THE VALVE SO THAT THE REMOTE CONTROL BUTTERFLY VALVE COULD BE USED IN THE LOW VELOCITY RUNS.

D. MANOMETERS

IT WAS NECESSARY TO CONSTRUCT TWO MICRO-MANOMETERS TO ACCURATELY MEASURE THE SLIGHT PRESSURE DIFFERENTIALS. A PHOTOGRAPH OF ONE OF THESE INSTRUMENTS WILL BE FOUND ON PAGE 10. THE PLANS FOR THE INSTRUMENTS WERE WORKED OUT AT GEORGIA TECH, BUT THEY WERE BASED ON A SIMILAR INSTRUMENT USED AT THE UNIVERSITY OF TORONTO[1]. THEY READ DIRECT TO ONE THOUSANDTH OF AN INCH OF ALCOHOL AND MAY BE ESTIMATED TO .0005 INCH OF ALCOHOL OR .0004 INCH OF WATER. A FULL DESCRIPTION OF THE MANOMETERS WILL BE FOUND IN THE APPENDIX.

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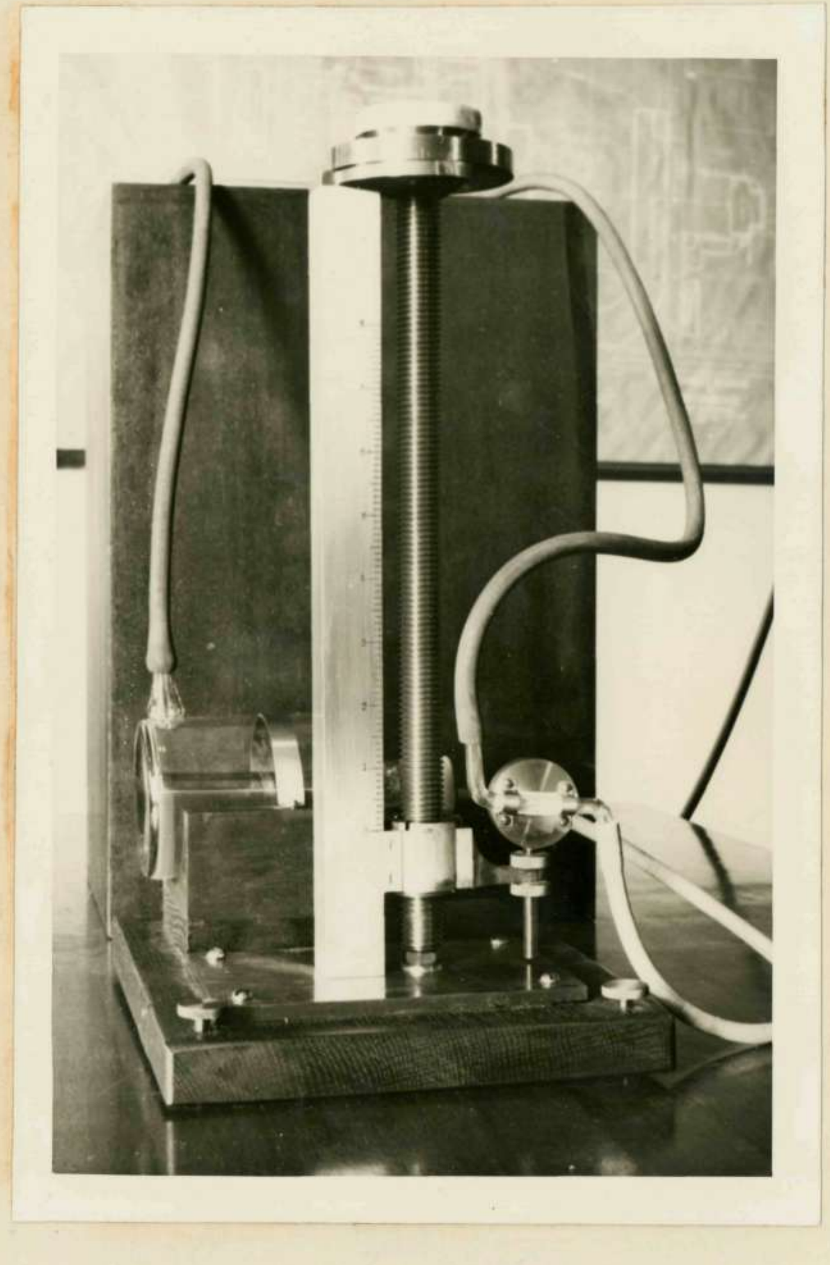
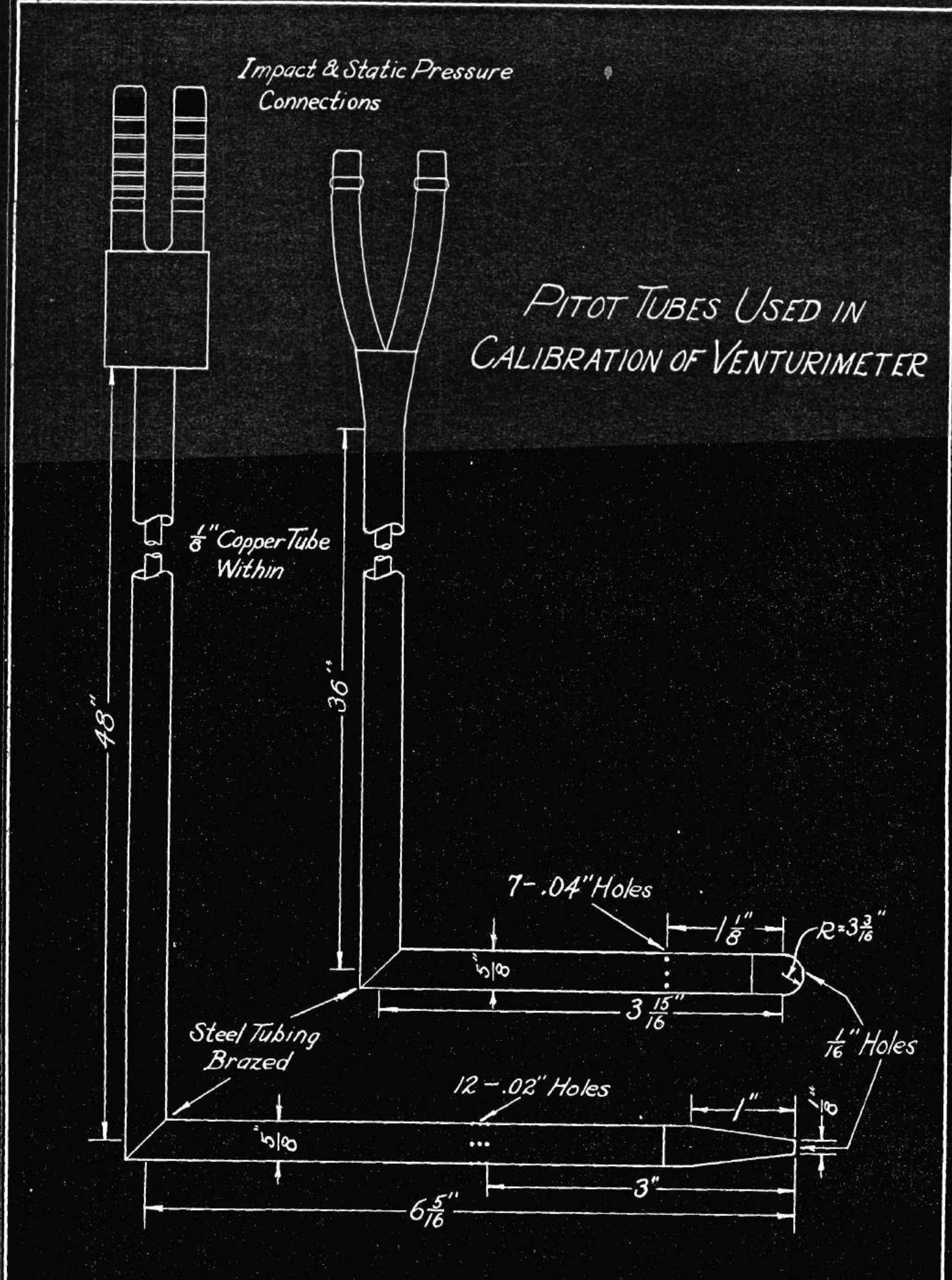
1. E. OWER-MEASUREMENT OF AIR FLOW - CHAPMAN & HALL LTD., LONDON - 1933



MICRO-MANOMETER


Impact & Static Pressure Connections
PITOT TUBES USED IN CALIBRATION OF VENTURIMETER
1/8" Copper Tube Within
48"
36"
7-.04" Holes
1 1/8"
R=3 3/16"
5/8"
3 15/16"
1/16" Holes
Steel Tubing Brazed
12-.02" Holes
1"
1/8"
5/8"
3"
6 5/16"

E. Pitot Tubes

The two pitot tubes used in calibrating the venturimeter were made in accordance to different standards of design so that one might be a check on the other. One tube was made especially for this test and proportioned as a recommended by the American Society of Mechanical Engineers.[1] The other tube, borrowed from The Aeronautics Department of the Georgia School of Technology, was designed from recommendations of the Aeronautical Research Committee of the National Physical Laboratory of England[2]. Calibration of these tubes is discussed in the Appendix and a drawing of them will be found on the preceding page.

F. Venturimeter

The Venturimeter used for determining the flow during actual test work had been in the laboratory for several years, but as it was of a poor design, it was revamped as much as possible for this test. It was made of galvanized sheet metal, and had a 22.83 inch approach and a 12.09 throat. Eight 1/8 inch static pressure taps were located at the throat and connected by a piezometer ring, and the same at the approach section.

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1. American Society of Mechanical Engineers Research Publication Third Edition - 1931 - <u>Fluid Meters, Their Theory and Application</u>.

2. E. Ower and F. C. Johansen - <u>Design of Pitot-Static Tubes</u> Reports of Memoranda, No. 981 of the Aeronautical Research Committee of the National Physical Laboratory of England.

As told in the appendix, this meter was painstakingly calibrated by 21 separate 20-point pitot tube traverses. Two different pitot tubes were used and traverses were made at different size sections brfore and after the venturimeter to average out *all possible* errors.

G. Intake Orifice Meter

Orifice Plates: The orifices used were of the thin plate, square edge type with round holes concentrically located with respect tot the pipe. They were made from galvanized sheet iron with an average thickness of .064 inches. The holes of four of them were turned on a lathe by fastening them to a wood panel, and any burrs were removed by a fine file.

A fifth orifice plate was made of the same metal by cutting with a cold chisel, to test the effect of roughness and ragged edges. This orifice was not touched with a file. The following table gives diameters (d) of the orifices and the ratio of their areas to that of the pipe (D = 22.75)

Table 1.

Plate No.	Diameter (d) inches	% Area $100(d/D)^2$
1.	10.18	20%
2.	12.50	30.2%
3.	15.25	45%
4.	18.33	65%
5.	18.28	64.55%
Pipe	22.78	100.1%

THE PLATE DENOTED AS "PIPE" REFERS TO THE TESTS IN WHICH NO PLATE WAS USED AT ALL, THE OPEN END OF THE PIPE SERVING AS AN "ORIFICE".

PIPE: THE PLATES WERE FASTENED BY 30 BOLTS TO A $3\frac{1}{2}$ INCH FLANGE SOLDERED TO THE OUTSIDE OF THE END OF THE PIPE. A FELT GASKET WAS USED TO PREVENT LEAKS. THIS SECTION OF THE DUCTWORK, 36 INCHES LONG, WAS MADE OF 16 GAGE GALVANIZED IRON WITH A REINFORCING RIM AT THE BACK TO INSURE A CIRCULAR SECTION. THE INSIDE DIAMETER THROUGHOUT THIS SECTION WAS 22.75 INCHES, WHILE AT THE FLANGE END THE INSIDE MEASURED 22.78 INCHES.

PRESSURE TAPS: SEVENTEEN PRESSURE TAPS WERE LOCATED AT APPROXIMATELY EACH TWO INCHES DOWNSTREAM FROM THE ORIFICE PLATE. EACH HOLE WAS OFFSET ONE INCH SUCCESSIVELY AROUND THE CIRCUMFERENCE SO THAT NO TWO HOLES WERE IN THE SAME STREAM LINE. THIS ELIMINATED THE POSSIBILITY OF TURBULENCE FORMED BY ONE STATIC HOLE AFFECTING THE SUCCEEDING PRESSURE READING. ALL STATIC HOLES WERE DRILLED ONE EIGHTH INCH IN DIAMETER AND SLIGHTLY BEVELED TO REMOVE BURRS. GAS COCKS WERE SOLDERED ON THE OUTSIDE OF THE PIPE AT EACH HOLE SO THAT A RUBBER HOSE CONNECTION COULD BE SHIFTED FROM TAP TO TAP AND THE ONES NOT IN USE TURNED OFF. THE COCKS WERE GROUND IN WITH VALVE COMPOUND, TESTED FOR LEAKS AND GREASED. ALL RUBBER HOSE USED WAS NEW HEAVY TUBING, AND WAS TESTED FOR LEAKS.

THE FOLLOWING TABLE GIVES THE EXACT LOCATION OF THE STATIC PRESSURE TAPS IN INCHES AND ALSO IN PER CENT PIPE DIAMETER. MEASUREMENTS WERE MADE FROM THE DOWNSTREAM SIDE OF THE ORIFICE PLATE TO THE CENTER OF THE STATIC PRESSURE HOLE.

LOCATION OF STATIC PRESSURE TAPS

TAP NO.	DISTANCE FROM PLATE	%D	TAP NO.	DISTANCE FROM PLATE	%D
1	2.13 IN.	9.37%	10	20.43 IN.	90.0%
2	4.12	18.1	11	22.50	98.9
3	6.16	27.1	12	24.53	107.9
4	8.18	36.0	13	26.58	117.0
5	10.22	45.0	14	28.61	126.0
6	12.26	54.0	15	30.64	135.0
7	14.30	63.0	16	32.67	143.8
8	16.33	71.9	17	34.69	152.6
9	18.38	80.8			

III. METHOD OF CONDUCTING TEST

A. LOCATION OF VENA CONTRACTA.

AFTER A CAREFUL CHECK TO REMOVE ANY AIR BUBBLES IN THE ALCOHOL CONNECTIONS OF THE MANOMETERS, THE BASES OF THE INSTRUMENTS WERE LEVELED WITH A SPIRIT LEVEL AND THE ZERO READINGS ACCURATELY SET. THE ANGLE OF THE CROSS-HAIR TUBE WAS ADJUSTED TO SUIT THE REQUIRED ACCURACY OF THE PARTICULAR RUN, VALUES OF FROM $1\frac{1}{2}$ TO 10 DEGREES BEING USED ACCORDING TO WHETHER THE READINGS WILL BE IN THE VICINITY OF 1/10 INCH OR 8 INCHES.

WITH A GIVEN ORIFICE PLATE IN PLACE, THE SLIDE VALVE ON THE FAN DISCHARGE WAS OPENED TO GIVE MAXIMUM FLOW FOR THE FIRST RUN. THE OPERATOR AT THE VENTURIMETER STATION KEPT THE FLOW AS CONSTANT AS POSSIBLE BY THE REMOTE CONTROL BUTTERFLY VALVE, AT THE SAME TIME SIGNALING IF THE FLOW BECAME TOO FAST OR TOO SLOW. IN SPITE AF ALL PRECAUTIONS TAKEN IT WAS IMPOSSIBLE TO MAINTAIN AN ABSOLUTELY STEADY RATE OF FLOW. HOWEVER, THE VARIATIONS WERE BROUGHT WITHIN NARROW LIMITS, AND AS EACH READING WAS RECORDED ONLY AFTER OBSERVATIONS WITH THE VELOCITY SLIGHTLY ABOVE AND SLIGHTLY BELOW, AS WELL AS NORMAL, THE ERROR HERE WAS REDUCED TO A MINIMUM.

STARTING WITH THE TAP NEAREST THE ORIFICE PLATE, THE DIFFERENCE IN PRESSURE FROM THE ATMOSPHERE WAS MEASURED BY THE MANOMETER. WITH THE FLUCTUATING FLOW THAT EXISTED IT REQUIRED SEVERAL MINUTES OBSERVATION TO GET A REPRESENTATIVE READING AT EACH POINT. ALSO, AT POINTS REMOTE FROM THE VENA CONTRACTA THERE WAS A CHARACTERISTIC UNSTABILITY IN PRESSURE,

ESPECIALLY IN THE DOWNSTREAM DIRECTION, THAT MADE READINGS DIFFICULT. IT WAS FOUND THAT THE READINGS BECAME MORE STABLE WITH DECREASED DIFFERENTIAL AND INCREASED ORIFICE SIZE WITH THE EXCEPTION OF THE 100% ORIFICE.

ON SOME OF THE RUNS, READINGS WERE NOT TAKEN ANY FURTHER FROM THE ORIFICE PLATE THAN ABOUT THE 3% RECOVERY POINT, AS THIS WAS AS MUCH AS WAS NEEDED FOR THIS INVESTIGATION.

AN ALTERNATE METHOD WAS USED WHERE THE FLOW WAS VERY UNSTEADY THAT PROVED VERY SATISFACTORY. THIS WAS TO ROUGHLY LOCATE THE VENA CONTRACTA, CONNECT THE LOW PRESSURE SIDE OF THE MANOMETER HERE AND READ THE DIFFERENTIAL PRESSURES BETWEEN THIS TAP AND THE OTHER TAPS. THE ADJACENT COCKS WERE TRIED FIRST AND IF ONE GAVE A NEGATIVE READING, THE LOW PRESSURE SIDE OF THE MANOMETER WAS SHIFTED TO IT. THIS ELIMINATED THE FLUCTUATIONS DUE TO VARYING RATES OF FLOW, AS A 1/4 % CHANGE IN VELOCITY WOULD CHANGE THE RELATIVE DIFFERENCE BETWEEN THE PRESSURE TAPS ONLY AN INSIGNIFICANT AMOUNT.

IN SOME INSTANCES WHERE READINGS WERE UNSTABLE, TWO OR MORE RUNS AT THE SAME VELOCITY WERE AVERAGED TO OBTAIN SMOOTH CURVES.

APPROXIMATELY SEVEN RUNS WERE MADE ON EACH OF THE SIX ORIFICE SIZES, USING DIFFERENT RATES OF FLOW. THESE RATES OF FLOW WERE SELECTED AT RANDOM, EXCEPT THAT RUNS WERE MORE CLOSELY SPACED AS THE DIFFERENTIAL BECAME LOWER SO THAT THEY WOULD BE MORE EQUALLY SPACED ON A VELOCITY BASIS.

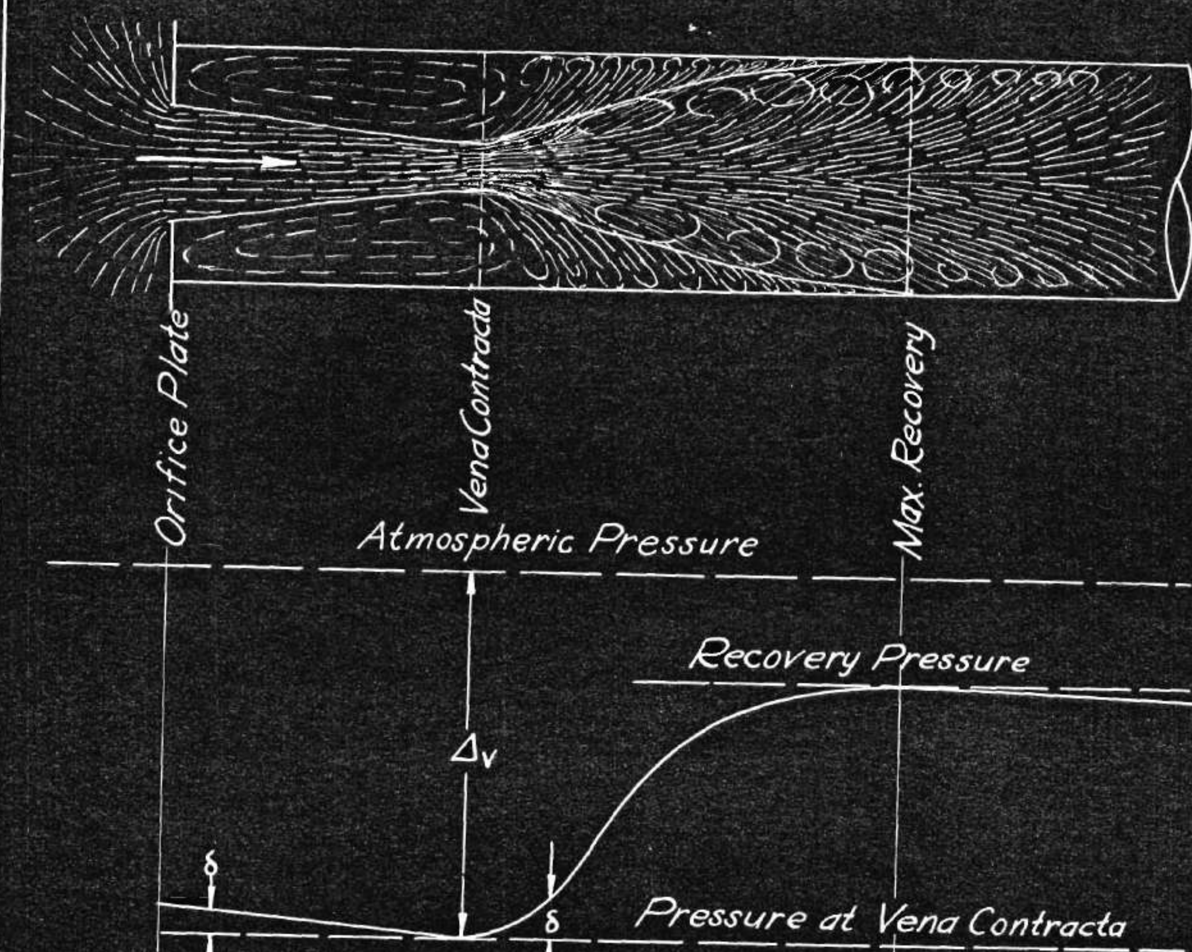
In the case of the 100% orifice, no orifice plate was used, the air being drawn directly into the pipe. The $3\frac{1}{2}$ inch external flange was left on as it could not be conveniently removed. The location of the vena contracta was so sharp in this case that the taps should have been located closer together for best results. Also, there was a slight ridge preceding the first tap which may have affected the reading somewhat. The readings for this 100% orifice were rather unsteady and its accuracy is not comparable to the other runs.

B. Coefficient of Discharge

The coefficients of discharge found in these experiments are based on the pressure differential at the vena contracta. Since this pressure was obtained in locating the vena contracta at known rates of flow, it was necessary to only supplement these readings with additional ones taken at other rates of flow, and also to make repeat readings at the same velocities to get average values and to find the probable consistancy or ability to repeat with the same results.

These repeat runs were made on different days at various temperatures, humidities and barometer readings.

CORRELATION OF FLOW THRU ORIFICE TO CHANGES IN STATIC PRESSURE



IV. RESULTS

A. LOCATION OF VENA CONTRACTA

THE FOLLOWING PAGES CONTAIN A TABULATION OF THE PRESSURES READ AT THE VARIOUS TAPS FOR DIFFERENT VELOCITIES AND ORIFICE SIZES. IN SOME CASES THE RESULTS RECORDED ARE THE AVERAGE OF TWO OR MORE RUNS. WHERE THE READINGS WERE ACTUALLY MEASURED AS DIFFERENCES IN PRESSURE FROM THAT AT THE VENA CONTRACTA, THEY WERE CONVERTED TO THE ACTUAL PRESSURE BELOW ATMOSPHERIC SO AS TO BE CONSISTANT. READINGS ARE IN INCHES OF ALCOHOL OF APPROXIMATE .802 SPECIFIC GRAVITY AT ROOM TEMPERATURES ENCOUNTERED. THE EXACT DENSITY MAY BE FOUND FROM THE CURVE ON PAGE 56 IN THE APPENDIX.

IN ORDER TO PUT THE RESULTS ON A COMPARATIVE BASIS, THE READINGS WERE ALL CONVERTED TO A PERCENT BASIS AS FOLLOWS:

Δ = PRESSURE AT ANY TAP (BELOW ATMOSPHERIC)

Δ_v = PRESSURE AT VENA CONTRACTA, OR DIFFERENTIAL

δ = DIFFERENCE IN PRESSURE AT ANY TAP FROM THAT AT VENA CONTRACTA

$$\delta = \Delta_v - \Delta$$

% DIFFERENCE FROM PRESSURE AT VENA CONTRACTA = $100 \frac{\delta}{\Delta_v}$

CURVES OF PERCENT DIFFERENCES WERE PLOTTED FOR VARIOUS VELOCITIES OR VALUES OF Δ_v, THOSE FOR EACH ORIFICE SIZE BEING GROUPED ON SEPARATE PAGES. TO SEPARATE THE CURVES, THE ZERO PER CENT LINE FOR EACH CURVE WAS SHIFTED UP THE SAME AMOUNT REGARDLESS OF THE DIFFERENCE IN VELOCITY.

PRESSURE GRADIENTS FOR ORIFICES

Pressures in inches of alcohol below atmospheric

20% Orifice Dia.= 10.18 in.

Tap No.	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$
	Vent.=.650		Vent.=.450		Vent.=.250		Vent.=.100		Vent.=.050	
	Dry Bulb 82		82		78		80		82	
	Wet Bulb 62		62		57		58		58	
	Bar. 28.90		28.90		28.80		28.86		28.86	
1	2.805	1.16	1.950	.92	1.079	1.46	.4397	.97	.227	.87
2	2.805	1.16	1.953	.76	1.086	.82	.440	.90	.2275	.66
3	2.811	.95	1.957	.56	1.087	.73	.4405	.79	.228	.44
4	2.814	.85	1.958	.51	1.090	.46	.4415	.57	.228	.44
5	2.816	.77	1.960	.41	1.092	.27	.442	.45	.2282	.35
6	2.823	.55	1.961	.36	1.093	.18	.442	.45	.2285	.22
7	2.824	.49	1.963	.25	1.095	0	.4432	.18	.2285	.22
8	2.829	.32	1.963	.25	1.094	.09	.4437	.07	.229	0
9	2.832	.21	1.964	.20	1.095	0	.444	0	.229	0
10	2.835	.10	19967	.05	1.095	0	.444	0	.2288	.09
11	2.837	.03	1.967	.05	1.094	.09	.442	.45	.2278	.52
12	2.838	0	1.968	0	1.091	.37	.440	.90	.2255	1.53
13	2.838	0	1.964	.20	1.086	.82	.437	1.58	.2238	2.27
14	2.825	.46	1.957	.56	1.077	1.46	.432	2.70	.221	3.50
15	2.813	.88	1.944	1.22	1.067	2.56	.428	3.60	.219	4.36
16	2.795	1.52	1.928	2.04	1.055	3.65	.423	4.74	.216	5.77
17	2.770	2.40	1.910	2.95	1.045	4.56	.418	5.86	.213	6.98
	2 Run	Av.	One	Run	Two Run	Av.	Two Run	Av.	Two Run	Av.

100% Orifice Dia.= 22.78 in.

Tap No.	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$
	Vent.= 7.000		Vent.=5.000		Vent= 2.500		Vent.= 1.250		Vent.=.750	
	Dry Bulb 92		84		84		83		86	
	Wet Bulb 68		65		65		64		68	
	Bar. 28.98		28.90		28.90		28.90		29.04	
1	1.185	1.82	.860	1.71	.432	3.14	.215	2.72	.131	2.82
2	1.207	0	.875	0	.446	0	.221	0	.1348	0
3	1.180	2.24	.858	1.94	.443	.67	.217	1.81	.130	3.56
4	1.120	7.20	.790	9.71	.415	6.95	.196	11.3	.120	11.0
5	1.020	15.5	.700	20.0	.360	19.3	.170	23.1	.105	22.1
6	.910	24.6	.630	28.0	.295	33.8	.150	32.1	.087	35.5
7	.820	31.2	.590	32.6	.274	38.5	.132	40.3	.078	42.2
8			.550	37.2	.270	39.4			.075	44.4
9			.530	39.4	.264	40.8			.073	45.9
10			.515	41.2	.255	42.8			.073	45.9
11			.500	42.4	.249	43.6			.073	45.9
12			.495	43.5	.245	45.0			.0725	46.3
13			.487	44.3	.244	45.2			.073	45.9
14			.482	44.9	.243	45.5			.072	46.6
15			.480	45.1	.242	45.65			.072	46.6
16			.476	45.5	.242	45.65			.072	46.6
17	.660	45.3	.478	45.4	.242	45.65			.073	45.9
	One Run		One	Run	One	Run	One	Run	One	Run

PRESSURE GRADIENTS FOR ORIFICES

Pressures in inches of alcohol below atmospheric

30% Orifice Dia.= 12.50 in.

Tap No.	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$
	Vent. 1.500		Vent. 1.000		Vent. .800		Vent. .700		Vent. .500	
	Dry Bulb 92			83		80		72.		77
	Wet Bulb 68			65		65		59		60
	Bar. 29.06		29.09		28.94		29.13		29.09	
1	2.848	1.25	1.913	1.19	1.533	1.03	1.335	1.26	.956	.88
2	2.855	1.00	1.925	.57	1.539	.65	1.339	.96	.958	.68
3	2.860	.83	1.928	.41	1.543	.39	1.341	.81	.959	.57
4	2.864	.69	1.930	.31	1.545	.26	1.343	.67	.960	.47
5	2.870	.49	1.932	.21	1.546	.19	1.346	.44	.9615	.31
6	2.874	.35	1.933	.16	1.547	.13	1.348	.30	.9625	.21
7	2.876	.28	1.934	.10	1.548	.06	1.350	.15	.9635	.10
8	2.878	.21	1.935	.05	1.549	0	1.351	007	.9645	0
9	2.881	.14	1.936	0	1.549	0	1.352	0	.9645	0
10	2.884	0	1.936	0	1.548	.06	1.352	0	.964	.05
11	2.884	0	1.936	0	1.545	.25	1.347	.37	.957	.78
12	2.880	.14	1.936	0	1.540	.58	1.336	1.18	.947	1.82
13	2.855	1.00	1.920	.83	1.532	1.10	1.325	2.00	.933	3.32
14	2.825	2.04	1.900	1.85	1.514	2.36	1.305	3.45	.920	4.66
15	2.785	3.42	1.870	3.41			1.285	4.95	.900	6.75
16	2.745	4.82								
17										
	One Run		One Run		Two Run Av.		Two Run Av.		One Run	

Tap No.	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$
	Vent. .350		Vent. .250		Vent. .160		Vent. .065	
	Dry Bulb 80			80		80		77
	Wet Bulb 63			63		63		60
	Bar. 29.09		29.09		29.09		28.87	
1	.676	1.02	.484	.82	.3115	1.10	.1290	.77
2	.677	.88	.485	.62	.3128	.70	.1293	.54
3	.6785	.66	.486	.41	.3138	.38	.1296	.31
4	.680	.44	.4868	.25	.3148	.06	.1300	0
5	.681	.29	.4875	.10	.3150	0	.1300	0
6	.6815	.22	.488	0	.3150	0	.1300	0
7	.6825	.07	.488	0	.3150	0	.1300	0
8	.683	0	.488	0	.3150	0	.1296	.31
9	.683	0	.487	.205	.3145	.16	.1291	.69
10	.680	.44	.484	.82	.311	1.27	.1277	1.77
11	.676	1.02	.477	2.26	.307	2.54	.1257	3.31
12	.622	3.08	.471	3.48	.303	3.81	.1227	5.61
13	.654	4.25	.463	5.12	.298	5.40	.1207	7.15
14							.1185	8.85
15							.1160	10.08
16							.1140	12.30
17							.1118	14.00
	One Run		Two Run Av.		Two Run Av.		Two Run Av.	

PRESSURE GRADIENTS FOR ORIFICES

Pressures in inches of alcohol below atmospheric

45% Orifice Dia.= 15.25 in.

Tap No.	Press.	% $\frac{\delta}{\Delta_v}$	Press.	%	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$
	Vent. 3.000		Vent. 1.50		Vent. 1.000		Vent. .600		Vent. .400	
	Dry Bulb 92			82		82		83		85
	Wet Bulb 70			66		66		66		66
	Bar. 28.82			28.92		28.92		28.93		28.93
1	2.569	1.37	1.291	1.45	.868	1.59	.523	1.32	.347	1.28
2	2.578	1.04	1.294	1.22	.872	1.13	.525	.94	.349	.71
3	2.583	.84	1.300	.76	.872	1.13	.526	.75	.3495	.52
4	2.583	.84	1.303	.53	.873	1.02	.527	.57	.3510	.01
5	2.587	.69	1.303	.53	.876	.68	.5275	.47	.3515	0
6	2.589	.61	1.305	.38	.879	.34	.5285	.28	.3515	0
7	2.599	.23	1.308	.15	.880	.23	.5300	0	.3510	.01
8	2.602	.11	1.310	0	.882	0	.5295	.09	.348	1.00
9	2.605	0	1.310	0	.880	.23	.523	1.32	.343	2.42
10	2.585	.65	1.295	1.15	.868	1.59	.516	2.64	.338	3.84
11	2.535	2.57	1.270	3.06	.845	4.20	.500	5.66	.326	7.26
12	2.495	4.10								
13	2.446	6.22								
14	2.375	8.70								
15										
	One	Run	One	Run	One	Run	One	Run	One	Run

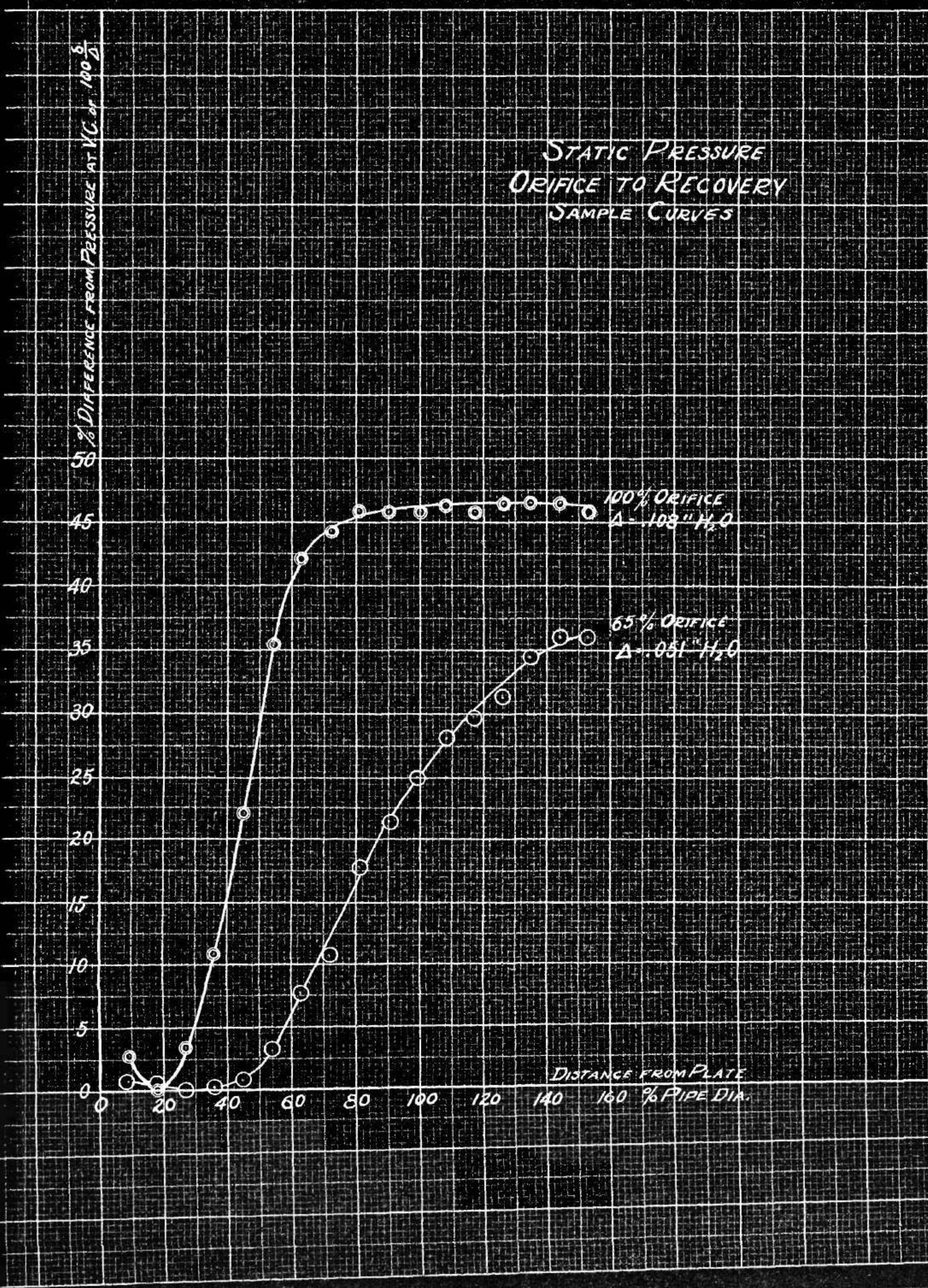
Tap No.	Press.	% $\frac{\delta}{\Delta_v}$	Press.	% $\frac{\delta}{\Delta_v}$
	Vent. .200		Vent. .100	
	Dry Bulb 82			80
	Wet Bulb 66			65
	Bar. 28.94			28.94
1	.175	.85	.0870	1.14
2	.176	.28	.0875	.57
3	.176	.28	.0875	.57
4	.176	.28	.0880	0
5	.1765	0	.0880	0
6	.1765	0	.0880	0
7	.176	.28	.0870	1.14
8	.173	1.98	.0860	2.28
9	.168	4.81	.0840	4.55
10	.164	7.08	.0810	7.95
11	.160	9.35	.0780	11.4
	One	Run	One	Run

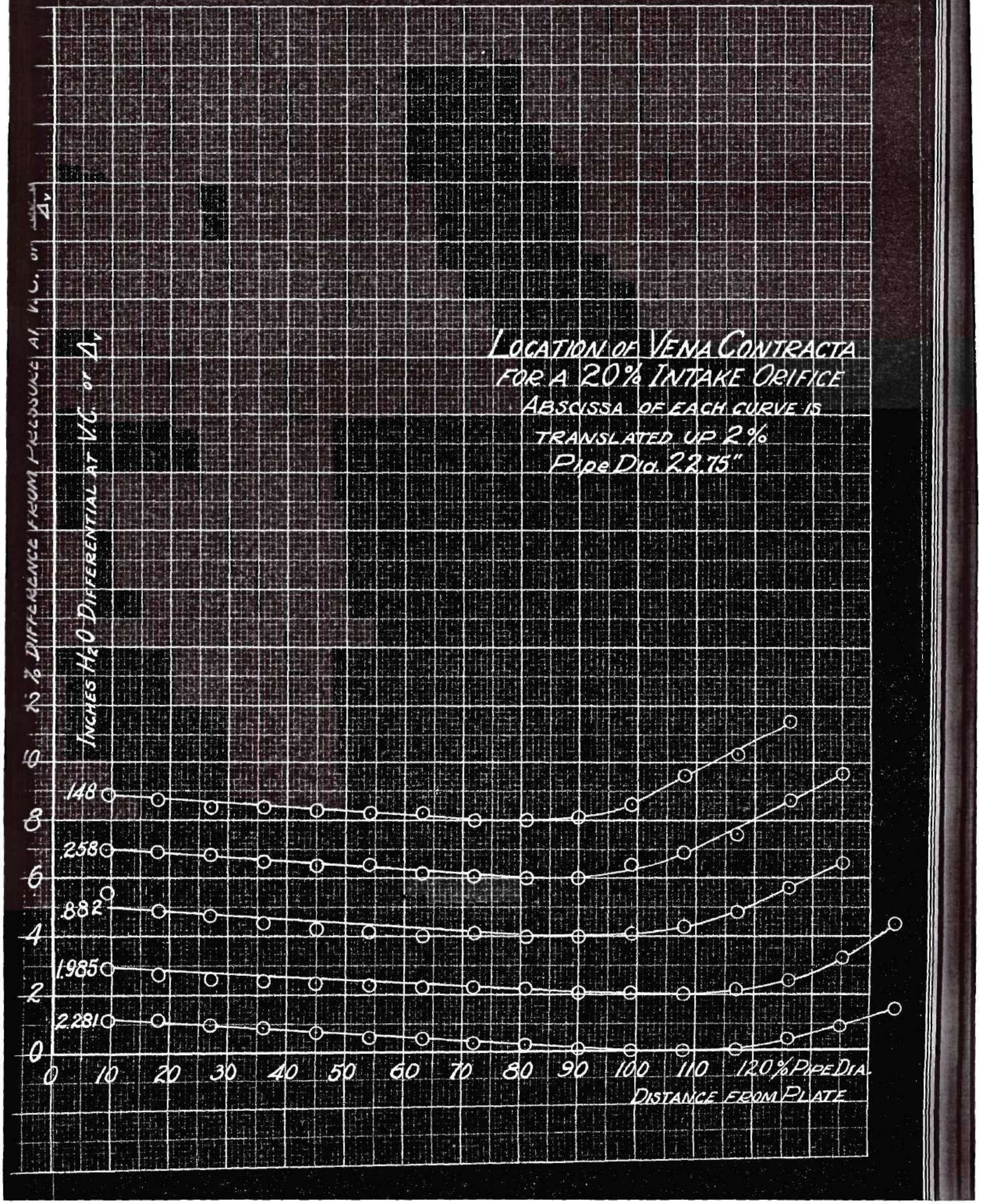
PRESSURE GRADIENTS FOR ORIFICES

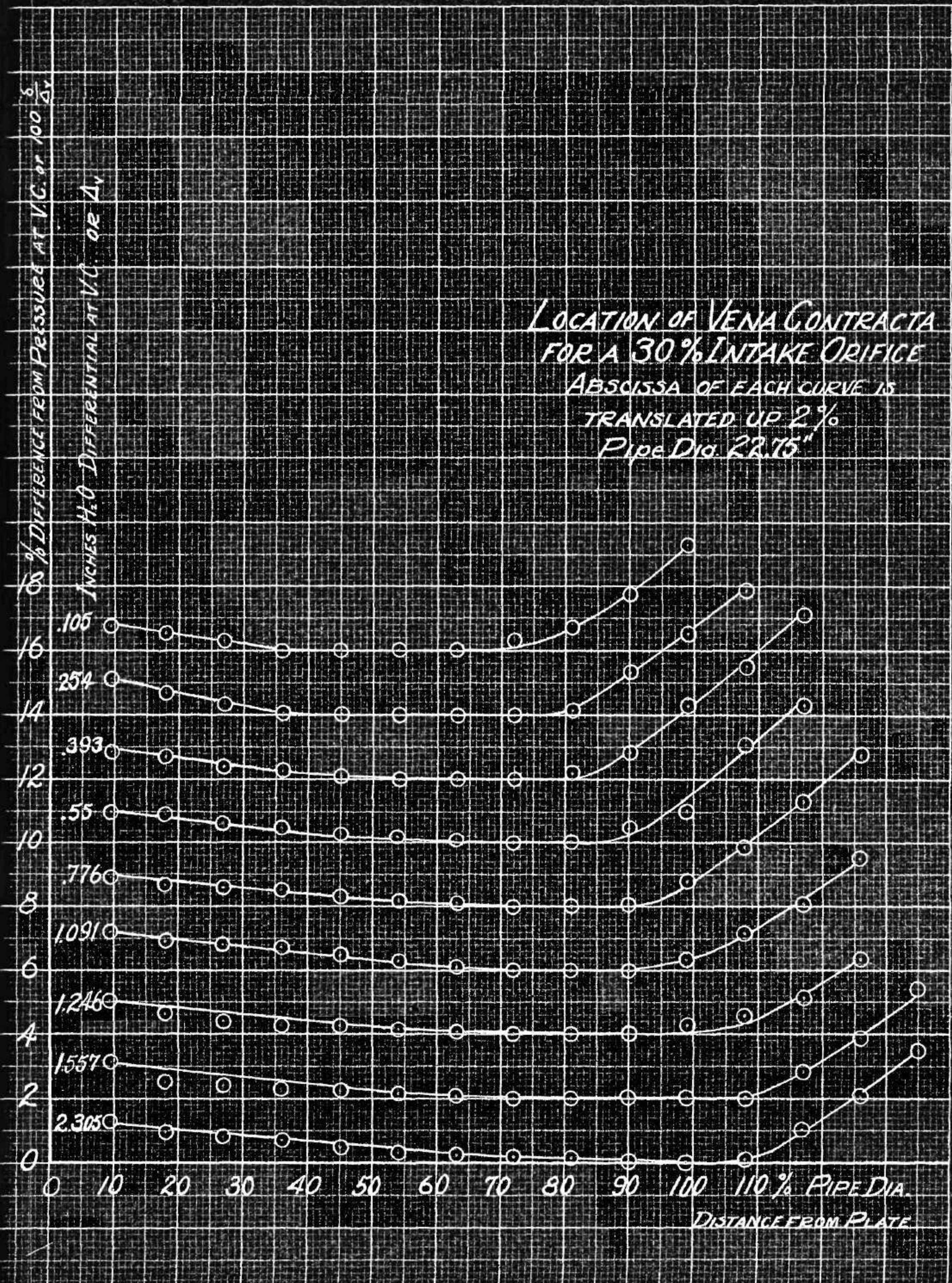
Pressures in inches of alcohol below atmospheric

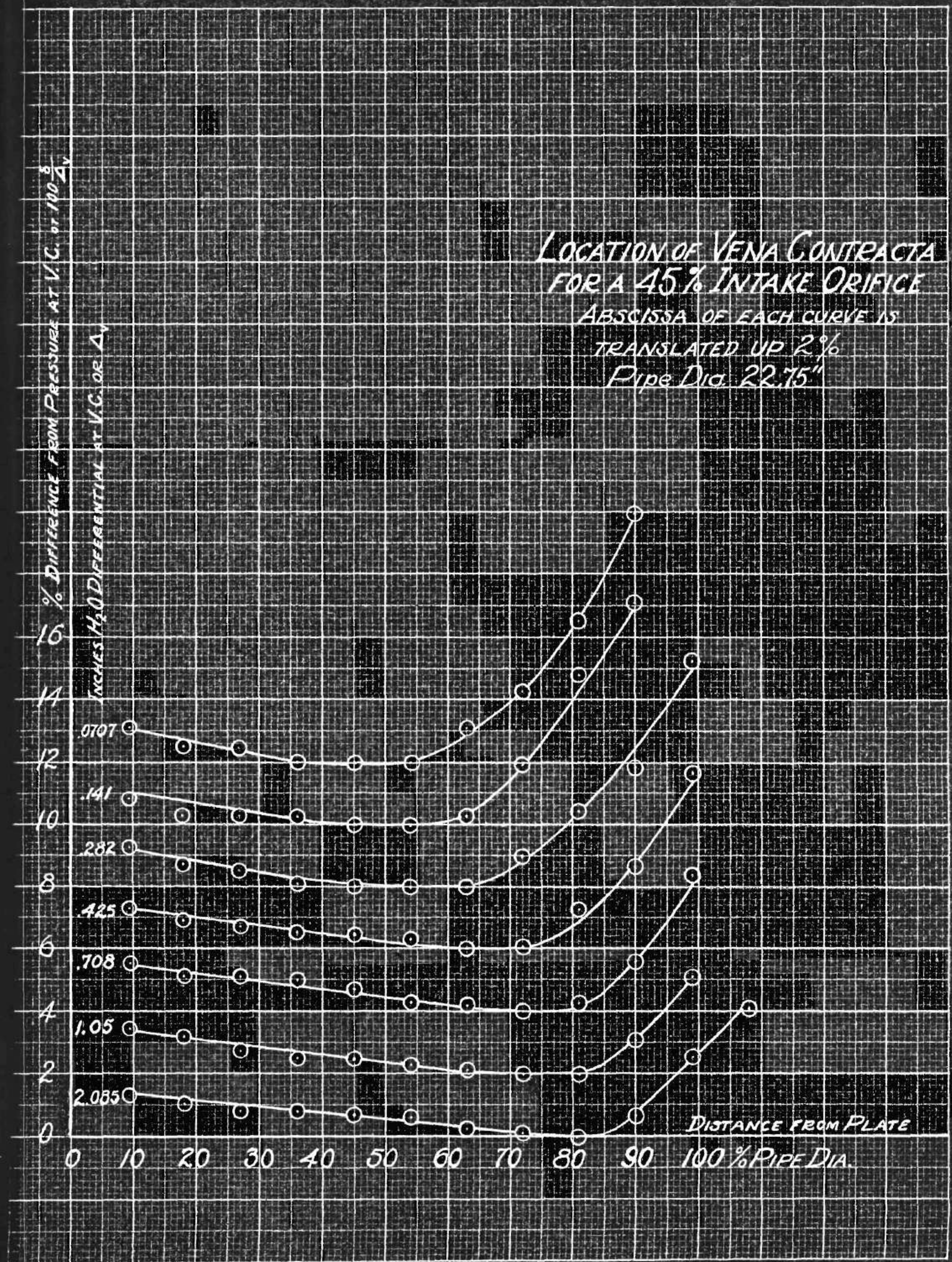
65% Orifice Dia.= 18.33 in.

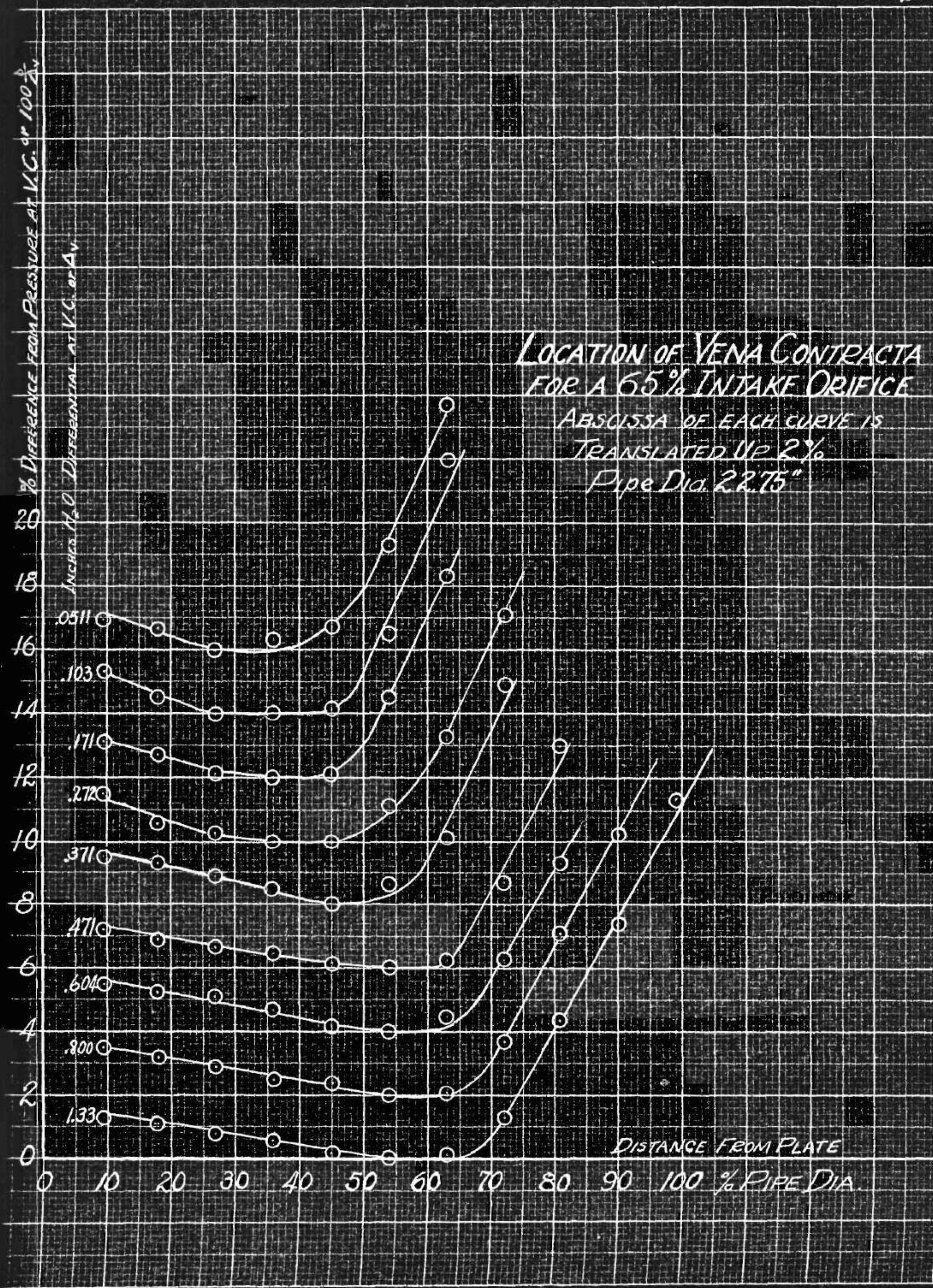
Tap No.	Press.	$\% \frac{\delta}{\Delta_v}$	Press.	$\% \frac{\delta}{\Delta_v}$	Press.	$\% \frac{\delta}{\Delta_v}$	Press.	$\% \frac{\delta}{\Delta_v}$	Press.	$\% \frac{\delta}{\Delta_v}$
	Vent. 4.000		Vent. 2.400		Vent. 1.800		Vent. 1.400		Vent. 1.100	
	Wet Bulb 65			58		61		58		62
	Dry Bulb 85			82		85		78		82
	Bar. 29.03			29.05		29.05		28.97		28.98
1	1.639	1.33	.982	1.51	.741	1.53	.579	1.21	.455	1.52
2	1.643	1.08	.985	1.20	.743	1.26	.581	.85	.456	1.30
3	1.648	.78	.988	.90	.744	1.06	.582	.68	.458	.87
4	1.651	.60	.992	.50	.7475	.66	.583	.51	.460	.43
5	1.658	.18	.993	.40	.751	.20	.585	.17	.462	0
6	1.661	0	.997	0	.7525	0	.586	0	.459	.65
7	1.659	.12	.996	.10	.749	.47	.5845	.26	.452	2.16
8	1.637	1.38	.980	1.70	.735	2.26	.570	2.73	.430	6.94
9	1.585	4.40	.946	5.12	.710	5.34	.545	7.0	.409	11.5
10	1.535	7.42	.915	8.23						
11	1.465	11.64			.640	14.9			.365	21.0
12	1.410	14.97	.820	17.8						
13	1.345	18.9			.575	23.6			.334	27.7
14	1.295	21.9	.745	25.3						
15	1.240	25.2			.530	25.9			.312	32.5
16	1.190	28.2								
17	1.160	30.5	.673	32.5	.500	33.5			.296	36.0
	Two Run Av.		One Run		Two Run Av.		One Run		Two Run Av.	
	Vent. .800		Vent. .500		Vent. .300		Vent. .150			
	Wet Bulb 64			62		62		65		
	Dry Bulb 85			85		85		82		
	Bar. 28.98			29.00		29.00		28.99		
1	.334	1.47	.211	1.17	.127	1.40	.0628	.94		
2	.337	.59	.212	.70	.128	.62	.0630	.63		
3	.338	.29	.2133	.09	.1288	0	.0634	0		
4	.339	0	.2135	0	.1288	0	.0632	.31		
5	.339	0	.2133	.09	.1285	.23	.0629	.79		
6	.335	1.18	.208	2.58	.1255	2.57	.0613	3.30		
7	.328	3.25	.200	6.33	.1185	8.00	.0585	7.70		
8	.315	7.08	.188	11.9	.112	13.2	.0565	10.8		
9	.291	14.2	.178	16.7	.107	17.1	.0520	17.9		
10	.		.		.102	21.0	.0500	21.5		
11	.266	21.1	.164	23.4	.097	24.8	.0475	25.1		
12							.046	28.2		
13	.244	28.0	.149	30.4	.088	31.8	.045	29.8		
14							.044	31.4		
15	.224	33.9	.140	34.6	.083	35.8	.042	34.4		
16							.041	36.1		
17	.213	37.2	.134	37.5	.079	38.8	.041	36.1		
	One Run		Two Run Av.		Two Run Av.		Two Run Av.			

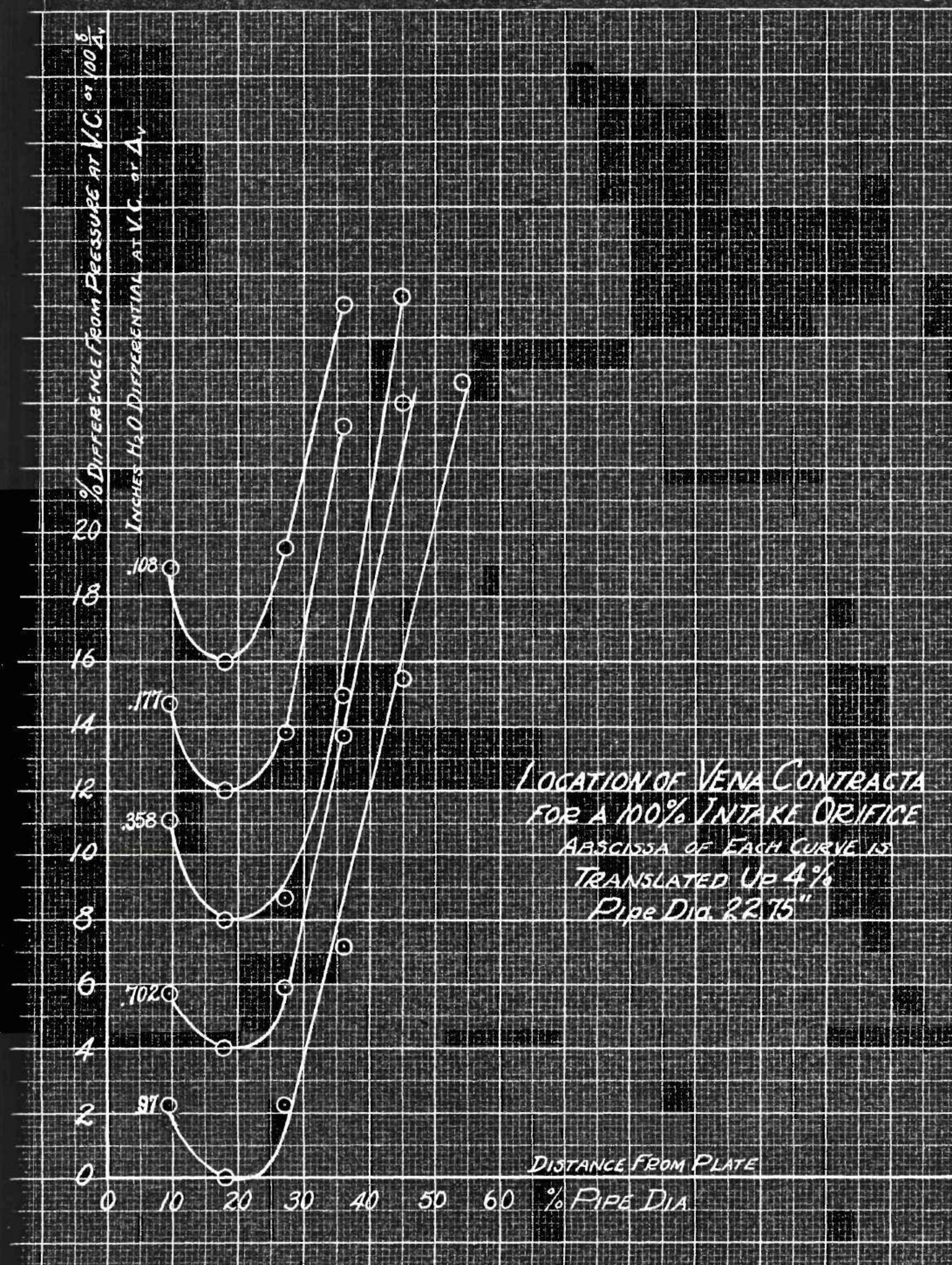

STATIC PRESSURE
ORIFICE TO RECOVERY
SAMPLE CURVES
% DIFFERENCE FROM PRESSURE AT V.C. OF $100 \frac{\delta}{\Delta}$
0
5
10
15
20
25
30
35
40
45
50
100% ORIFICE
Δ - .108" H_2O
65% ORIFICE
Δ - .051" H_2O
DISTANCE FROM PLATE
0
20
40
60
80
100
120
140
160 % PIPE DIA.


LOCATION OF VENA CONTRACTA
FOR A 20% INTAKE ORIFICE
ABSCISSA OF EACH CURVE IS
TRANSLATED UP 2%
Pipe Dia. 22.75"
INCHES H_2O DIFFERENTIAL AT V.C. OR Δ_v
% DIFFERENCE FROM PRESSURE AT V.C. OR Δ_v
.148
.258
.882
1.985
2.281
0
2
4
6
8
0 10 20 30 40 50 60 70 80 90 100 110 120% PIPE DIA.
DISTANCE FROM PLATE

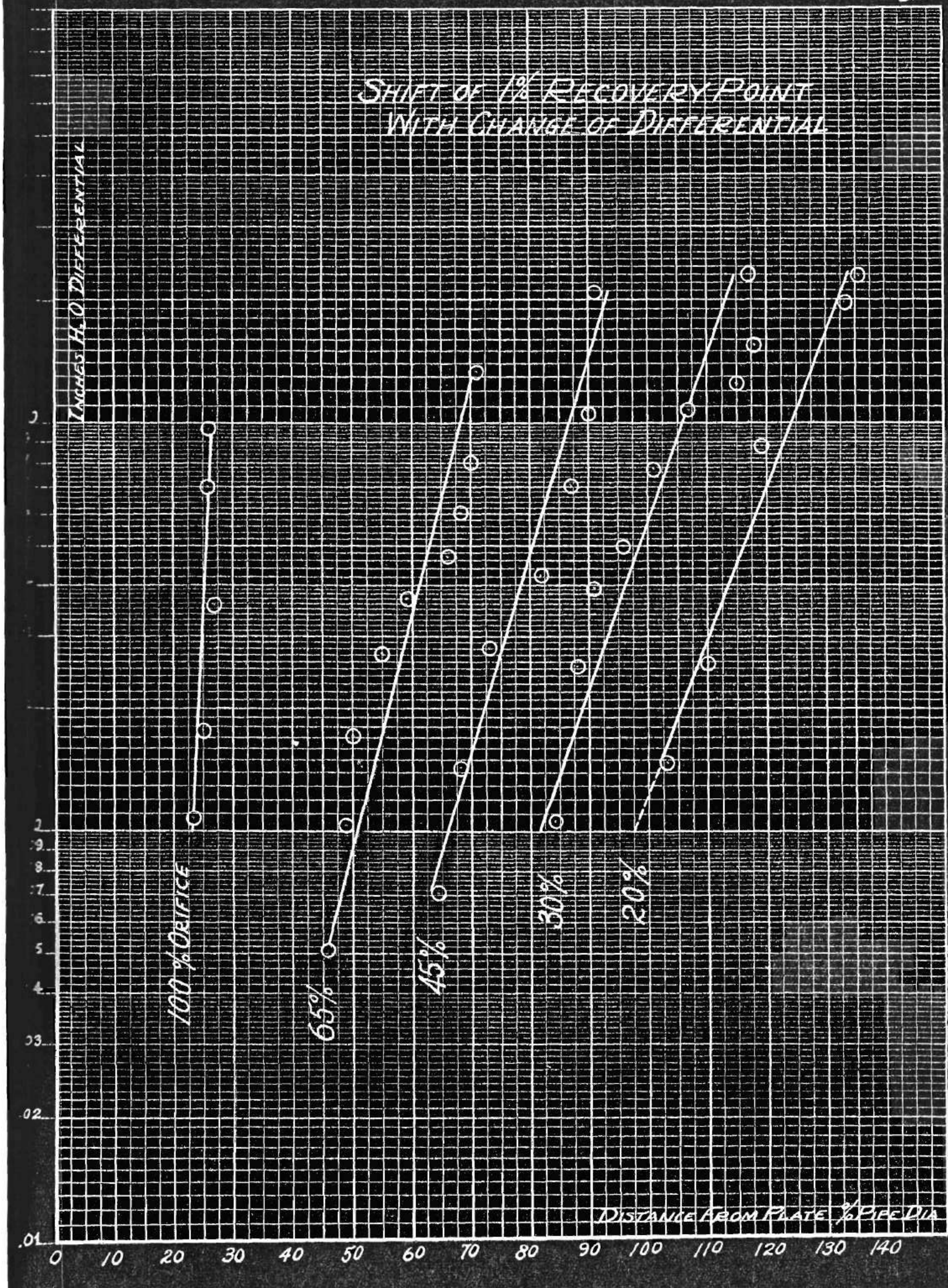

LOCATION OF VENA CONTRACTA
FOR A 30% INTAKE ORIFICE
ABSCISSA OF EACH CURVE IS
TRANSLATED UP 2%
Pipe Dia. 22.75"
% DIFFERENCE FROM PRESSURE AT V.C. or $100\frac{\delta}{\Delta_v}$
INCHES H_2O DIFFERENTIAL AT V.C. OR Δ_v
.105
.254
.393
.55
.776
1.091
1.246
1.557
2.305
0
2
4
6
8
10
12
14
16
18
0
10
20
30
40
50
60
70
80
90
100
110 % PIPE DIA.
DISTANCE FROM PLATE


LOCATION OF VENA CONTRACTA
FOR A 45% INTAKE ORIFICE
ABSCISSA OF EACH CURVE IS
TRANSLATED UP 2%
Pipe Dia. 22.75"
% DIFFERENCE FROM PRESSURE AT V.C. or $100\frac{\delta}{\Delta_V}$
INCHES H_2O DIFFERENTIAL AT V.C. OR Δ_V
.0707
.141
.282
.425
.708
1.05
2.085
0
2
4
6
8
10
12
14
16
DISTANCE FROM PLATE
0 10 20 30 40 50 60 70 80 90 100% PIPE DIA.


LOCATION OF VENA CONTRACTA
FOR A 65% INTAKE ORIFICE
ABSCISSA OF EACH CURVE IS
TRANSLATED UP 2%
Pipe Dia. 22.75"
% DIFFERENCE FROM PRESSURE AT V.C. or 100% Av
INCHES H2O DIFFERENTIAL AT V.C. or Av
.0511
.103
.171
.272
.371
.471
.604
.800
1.33
0
2
4
6
8
10
12
14
16
18
20
DISTANCE FROM PLATE
0 10 20 30 40 50 60 70 80 90 100 % PIPE DIA.


% Difference From Pressure at V.C. or 100 δ/Δv
Inches H2O Differential at V.C. or Δv
20
18
16
14
12
10
8
6
4
2
0
.108
.177
.358
.702
.97
0
10
20
30
40
50
60
% Pipe Dia.
Distance From Plate
Location of Vena Contracta
for a 100% Intake Orifice
Abscissa of Each Curve is
Translated Up 4%
Pipe Dia. 22.75"

It will be noticed that there is an unmistakable shift of the pressure recovery lines and also of the point of minimum pressure for different values of with the same orifice. Also, the shift is much more rapid at slight differential pressures. To show this shift, the location of the 1% pressure recovery point was plotted against the differential pressure on page 32. This point was selected rather than the position of the vena contracta since the former may be definitely located whereas the latter is rather indefinite and the judgment of the one plotting the curves may affect the position selected a distance of as much as 10 or 20% of the pipe diameter. Attempts were made to plot these curves of the shift of pressure recovery on regular coordinate paper and also on log paper, but semi log paper was used as this seemed to suit the curve best. It must be borne in mind that these curves were plotted to show the approximate actual location and shift of the 1% recovery point in this range of differentials, and the curves should not be extrapolated very far or taken to indicate that the trend will continue in the same direction for widely different differentials. Although the points on these curves may appear ragged, no point misses its curve over about 7% of the pipe diameter while most of the points are much closer. It must be remembered that these points represent a 1% change in pressures as small as .051 inch of water, which means a difference in pressure of only .00051 inch of water which is an extremely difficult measurement.


SHIFT OF 1% RECOVERY POINT
WITH CHANGE OF DIFFERENTIAL
INCHES H. O DIFFERENTIAL
100 % ORIFICE
65%
45%
30%
20%
DISTANCE FROM PLATE % PIPE DIA
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
.01
.02
.03
.4
.5
.6
.7
.8
.9
2

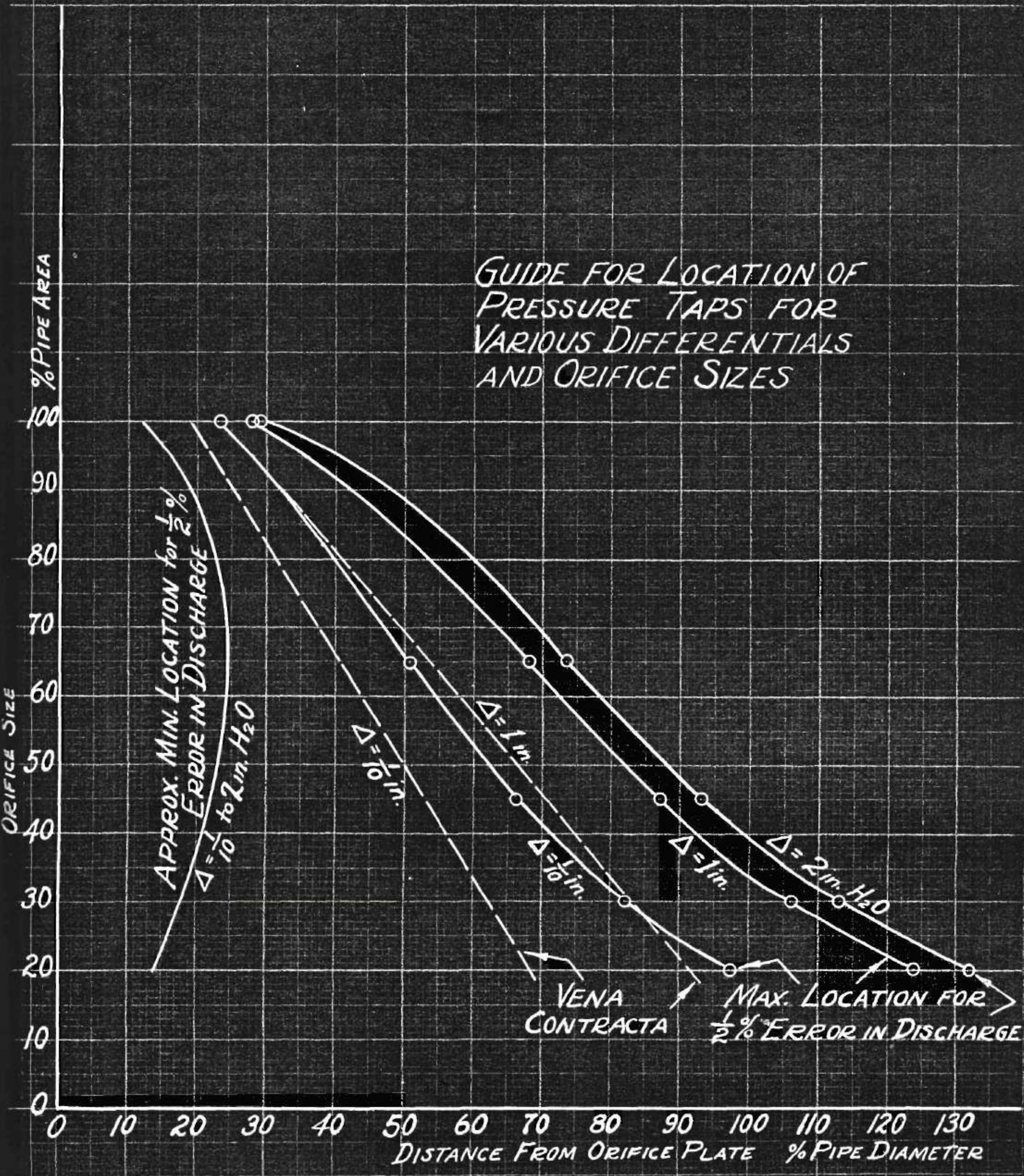
In order to correlate the results of different velocities and different orifice sizes, the curves on page 34 were plotted. The curves of maximum location of taps to be within ½% error in the flow through the orifice were plotted from values taken from the curves on page 32. One per cent error in reading the differential pressures means only ½% error in the flow calculated, as the flow is a function of the square root of the head, e.g.,

$$\sqrt{1.} = 1$$
$$\sqrt{.99} = .995$$

Although the difference between 1 and .99 is 1%, 1 and .995 are only ½% at variance.

Dotted lines show the approximate location of minimum pressure readings which were estimated from the position of this point on the original per cent pressure change curves. The location for a two inch differential was not shown as it would be displaced only slightly to the right of the curve for a one inch differential. Although this was labeled the location of the vena contracta and it is generally conceded by other experimenters that the plane of minimum pressure and vena contracta coincide, no proof of this correlation was made in these tests.

The approximate minimum location of the static pressure tap for ½% error in discharge was determined from the original per cent pressure change curves, the points being taken where the original curves intersect the 1% pressure difference lines in the upstream direction. These points were rather indefinite since the pressure change on the up-


GUIDE FOR LOCATION OF
PRESSURE TAPS FOR
VARIOUS DIFFERENTIALS
AND ORIFICE SIZES
% PIPE AREA
ORIFICE SIZE
100
90
80
70
60
50
40
30
20
10
0
APPROX. MIN. LOCATION for ½% ERROR IN DISCHARGE
Δ = 1/10 to 2 in. H2O
Δ = 1/10 in.
Δ = 1 in.
Δ = 1/10 in.
Δ = 1 in.
Δ = 2 in. H2O
VENA
CONTRACTA
MAX. LOCATION FOR
½% ERROR IN DISCHARGE
0
10
20
30
40
50
60
70
80
90
100
110
120
130
DISTANCE FROM ORIFICE PLATE % PIPE DIAMETER

STREAM SIDE OF THE VENA CONTRACTA IS VERY GRADUAL. THE CURVE SHOWN IS AN APPROXIMATION RATHER THAN AN AVERAGE OF ACTUAL VALUES, AND IS DRAWN FOR A 2 INCH DIFFERENTIAL, AS THE MINIMUM LOCATION FOR SMALLER DIFFERENTIALS WOULD BE NEARER THE ORIFICE PLATE.

IN USING THE INTAKE PIPE ORIFICE, FOR STEADIEST READINGS AND MOST ACCURATE RESULTS, THE STATIC PRESSURE TAP SHOULD BE LOCATED AT THE VENA CONTRACTA SHOWN BY THE DOTTED LINE, BUT AS THIS LINE SHIFTS WITH THE DIFFERENTIAL AS WELL AS WITH ORIFICE SIZE, OBVIOUSLY THIS WOULD BE IMPOSSIBLE FOR VARYING FLOW. HOWEVER, IT WILL BE SEEN FROM THE CURVES ON PAGE 34 THAT A LOCATION THAT IS IDEAL FOR A 1/10 INCH DIFFERENTIAL WOULD ALSO BE SATISFACTORY FOR A ONE INCH DIFFERENTIAL. HENCE, IF THE RANGE OF DIFFERENTIAL PRESSURES EXPECTED WERE FROM 1/10 TO ONE INCH THE TAP COULD BE LOCATED ON THE 1/10 INCH VENA CONTRACTA LINE; OR IF THE RANGE BE ONE INCH TO TWO INCHES OF WATER DIFFERENTIAL, A TAP LOCATED AT THE VENA CONTRACTA FOR A ONE INCH DIFFERENTIAL WOULD GIVE EXCELLENT RESULTS.

IN CASE IT IS DESIRED TO USE VARIOUS ORIFICES SIZES ON A PIPE AS WELL AS A WIDE RANGE OF DIFFERENTIALS, A TAP LOCATED 40% OF THE PIPE DIAMETER DOWNSTREAM WOULD GIVE GOOD RESULTS UP TO AN ORIFICE SIZE OF 80% OF ABOUT 9/10 OF THE PIPE DIAMETER.

ALTHOUGH THIS INVESTIGATION WAS MAINLY FOR DIFFERENTIALS ON ONE INCH AND LESS, WHERE POSSIBLE THE PRESSURE CHANGE WAS FOUND AND PLOTTED FOR VALUES UP TO TWO INCHES AND OVER. SINCE THE AMOUNT OF SHIFT DECREASED SO RAPIDLY WITH INCREASED DIFFERENTIALS, IT IS BELIEVED THAT THE TAP LOCATION SUITABLE FOR A TWO INCH DIFFERENTIAL WOULD BE SUITABLE FOR MUCH GREATER AIR VELOCITIES. THIS IS BORNE OUT BY THE FACT THAT OTHER EXPERI-

MENTERS HAVE FOUND NO APPRECIABLE SHIFT IN THE VENA CONTRACTA WITH VELOCITY IN PIPE ORIFICES FOR DIFFERENTIALS ABOVE ONE INCH OF WATER.

B. COEFFICIENT OF DISCHARGE

THE COEFFICIENTS FOUND ARE OVERALL HYDRAULIC COEFFICIENTS OF DISCHARGE BASED ON PRESSURE DIFFERENTIALS MEASURED AT THE VENA CONTRACTA.

$$V = CA\sqrt{2GH}$$

V = CU. FT. PER SEC.

C = OVERALL ORIFICE COEFFICIENT

A = AREA OF ORIFICE PLATE - SQ. FT.

G = ACCELERATION OF GRAVITY-FT.PER SEC.^{2}

H = HEAD IN FEET OF FLUID FLOWING

THIS IS THE ACCEPTED FORMULA FOR PRESSURE DIFFERENTIALS UP TO ONE PER CENT OF THE ABSOLUTE PRESSURE OF THE MEDIUM FLOWING. ALTHOUGH IT IS BASED ON THE ASSUMPTION THAT THE FLUID FLOWING IS NOT COMPRESSIBLE, ITS USE FOR AIR IS JUSTIFIED IN THAT WHEN USING THIS RELATION FOR A DIFFERENTIAL OF 1% OF THE ABSOLUTE PRESSURE, A DIFFERENCE OF ONLY .6% WILL BE FOUND FROM THE FLOW GIVEN BY THE COMPLETE THERMO-DYNAMIC EQUATION. AS THE HIGHEST ORIFICE DIFFERENTIAL USED IN THESE TESTS WAS 2.3 INCHES OF WATER, REPRESENTING LESS THAN .6% OF THE BAROMETRIC PRESSURE, IT IS WELL WITHIN THE RANGE OF USE OF THIS FORMULA.

$$C = \frac{\text{ACTUAL DISCHARGE}}{\text{THEORETICAL DISCHARGE}}$$

ACTUAL DISCHARGE IS FOUND BY THE VENTURIMETER AS FOLLOWS:

$$V = C_V A_V \sqrt{2GH_V}$$

C_V = OVERALL COEFFICIENT OF VENTURIMETER.

A_V = AREA OF VENTURIMETER THROAT—SQ. FT.

SUBSCRIPT $_V$ PERTAINS TO VENTURIMETER.

SUBSCRIPT $_O$ PERTAINS TO ORIFICE.

HENCE:

$$C = \frac{C_V A_V \sqrt{2GH_V}}{A_O \sqrt{2GH_O}}$$

$$\text{BUT } H = \frac{P \times S.G.}{12} \times \frac{62.43}{D}$$

P = DIFFERENTIAL IN INCHES OF ALCOHOL

S.G. = SPECIFIC GRAVITY OF ALCOHOL

D = DENSITY OF AIR

SUBSTITUTING:

$$C = \frac{C_V \frac{\pi D_V^2}{4} \sqrt{2G\frac{P_V}{12} \times SG_V \times \frac{62.43}{D_V}}}{\frac{\pi D_O^2}{4} \sqrt{2G\frac{P_O}{12} \times SG_O \times \frac{62.43}{D_O}}}$$

BUT $SG_V = SG_O$ (SAME ALCOHOL AT SAME TEMP.)

$D_V = D_O$ (SAME AIR, SAME TEMP., PRESSURE WITHIN 1%)

CANCELING ALL EQUAL TERMS:

$$C = \frac{C_V D_V^2 \sqrt{P_V}}{D_O^2 \sqrt{P_O}}$$

THE READINGS TAKEN FOR FINDING THE COEFFICIENTS, THEIR AVERAGES, AND THE CORRESPONDING COEFFICIENTS ARE TABULATED ON THE FOLLOWING PAGES.

THE COEFFICIENTS ARE PLOTTED ON PAGE 40 AGAINST DIFFERENTIAL PRESSURE AND AS SEEN, THE DOTTED LINE AT .601 COMES WITHIN .8% OF ALL 46 POINTS SAVE ONE. THERE IS APPARENTLY NO CHANGE IN COEFFICIENT WITH DIFFERENTIAL.

THE AVERAGE COEFFICIENT OF EACH ORIFICE PLATE WAS

COEFFICIENTS OF INTAKE PIPE ORIFICES

Pressures in inches of alcohol below atmospheric

20% Orifice Dia.= 10.18 in.

Venturimeter	.650	.450	.250	.100	.050
Tap No. Used	11 & 12	11& 12	9	9	8
Orifice Dif.	2.835	1.967	1.095	.444	.229
	2.840	1.969	1.097	.446	.229
			1.094	.449	.2285
					.2295
Average	2.838	1.968	1.095	.446	.229
Orifice Coeff.	.605	.606	.608	.606	.600

30% Orifice Dia.= 12.50 in.

nt.	1.500	1.000	.800	.700	.500	.350	.250	.16	.075	.065
ap	10	9	9	9	9	9	8	8	7	7
if.	2.884	1.936	1.549	1.352	.9645	.683	.488	.315	.149	.130
	2.886	1.935	1.548	1.359	.969	.685	.492	.316		.1307
		1.937	1.548	1.358	.970		.491			.1305
		1.938	1.549				.491			.131
v.	2.885	1.9365	1.5485	1.356	.9678	.684	.4905	.3155	.149	.1306
oeff.	.601	.601	.602	.603	.605	.603	.603	.6035	.602	.600

45% Orifice Dia.= 15.25 in.

Vent.	3.000	1.500	1.000	.600	.4000	.2000	.100
Tap	8	8	8	7	6	6	6
Dif.	2.605	1.310	.882	.530	.3515	.1765	.088
	2.602	1.307	.878	.530	.352	.177	.089
	2.603	1.305	.880	.530	.353	.1765	.089
	2.600				.351		
Av.	2.6025	1.307	.880	.530	.3519	.1767	.0887
Coeff.	.600	.600	.600	.601	.604	.605	.605

COEFFICIENTS OF INTAKE PIPE ORIFICES
Pressures in inches of alcohol below atmospheric

65% Orifice Dia.= 18.33 in.

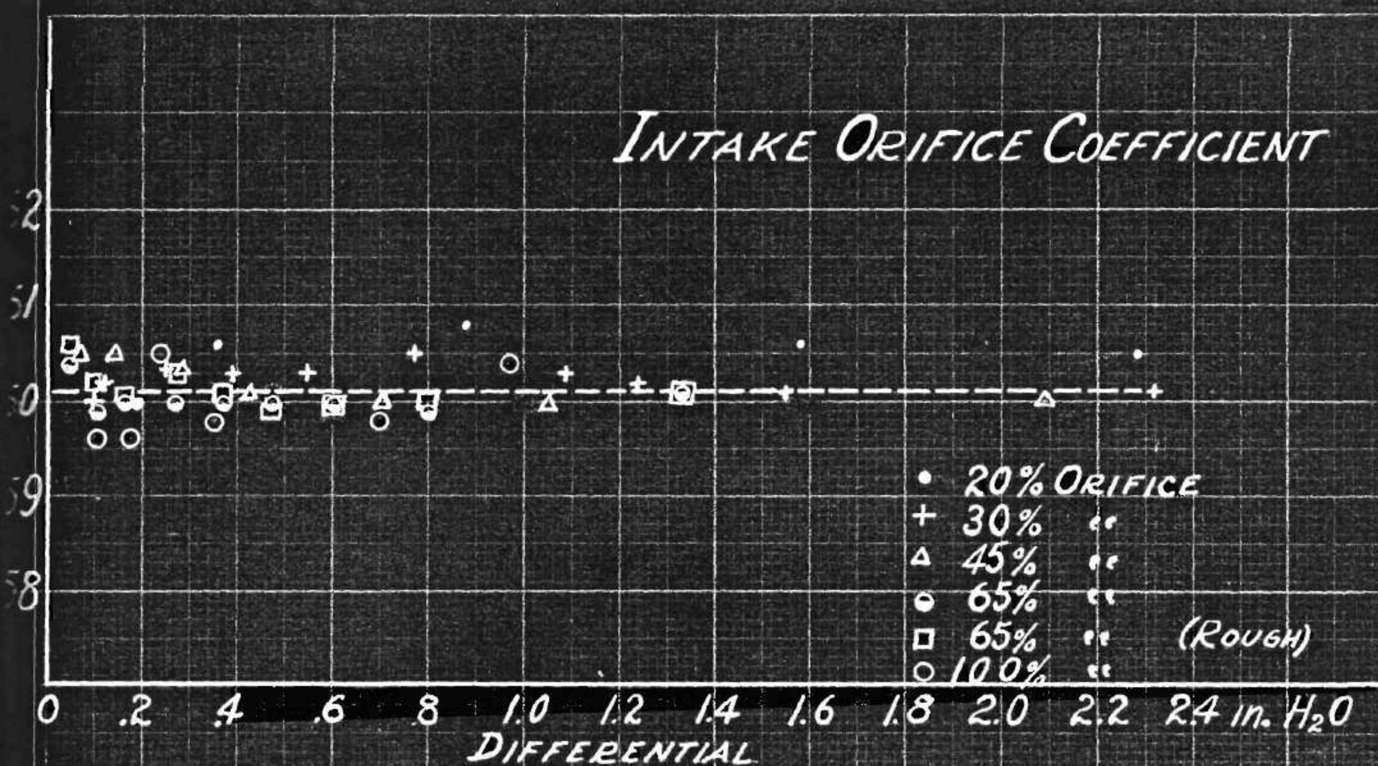
Vent.	4.000	2.400	1.800	1.400	1.100	.800	.500	.300	.150
Tap	6	6	6	6	6	6	5	4	4 & 3
Dif.	1.656	.997	.7525	.586	.462	.339	.2135	.1288	.0634
	1.658	.996	.7515	.586	.462	.337	.212	.1285	.0635
	1.665	.996	.7525	.586	.462	.337	.213	.1290	.0640
	1.655	.998						.1288	
	1.656	1.000							
Av.	1.658	.9974	.7522	.586	.4620	.3377	.2128	.1288	.0636
Coeff.	.601	.599	.600	.600	.600	.600	.600	.599	.604

65% Orifice Dia.= 18.28 in.
(Cut with cold chisel)

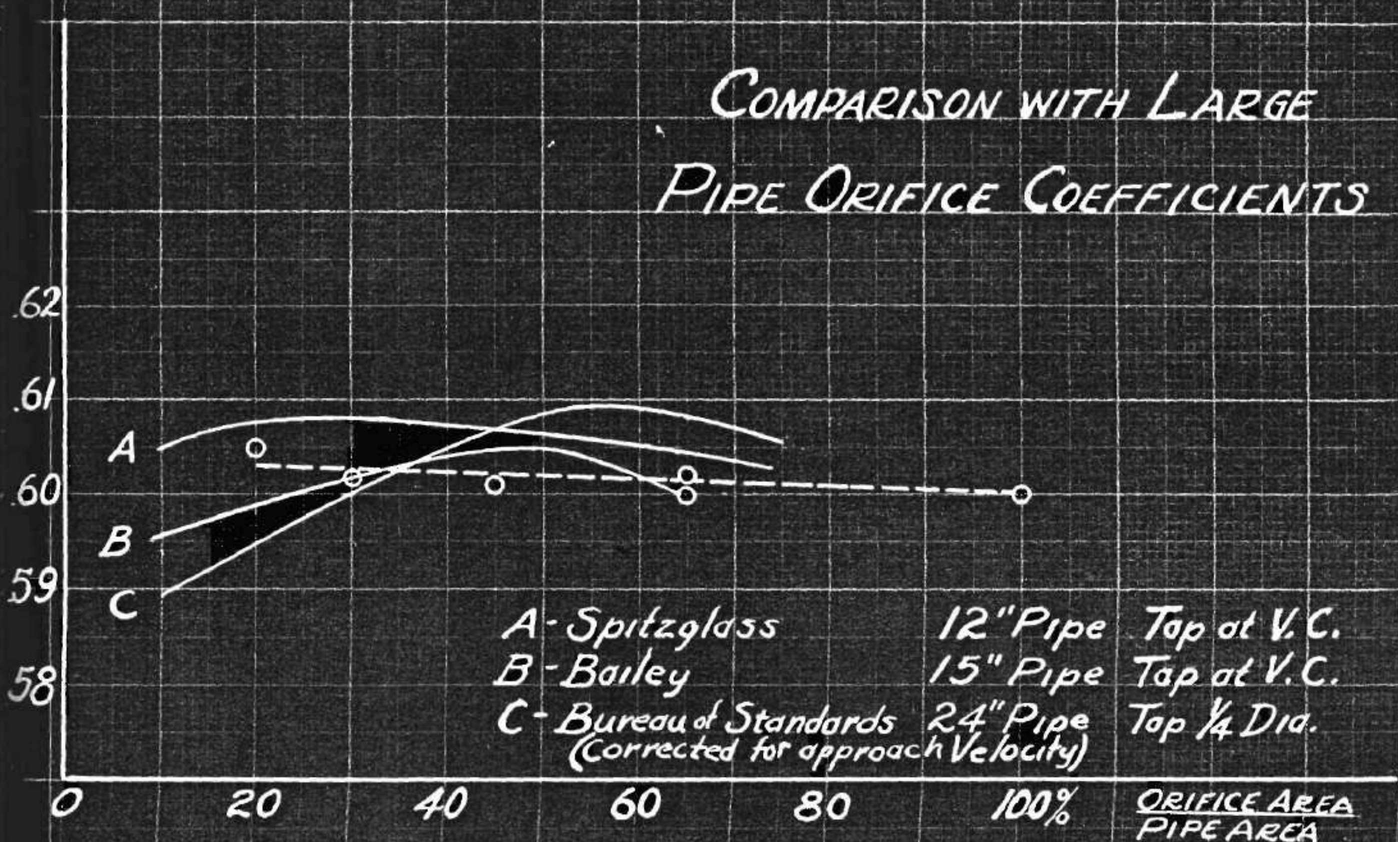
Vent.	4.000	2.400	1.800	1.400	1.100	.800	.500	.300	.150
Tap	6	6	6	6	5	5	4	4	4 & 3
Dif.	1.677	1.005	.760	.595	.464	.337	.215	.129	.0635
	1.677	1.008	.757	.595	.466	.338	.215	.129	.0645
		1.007	.759		.466	.339	.214		.0640
Av.	1.677	1.0066	.7587	.595	.4653	.338	.2147	.129	.0640
Coeff.	.601	.600	.600	.599	.601	.603	.601	.602	.606

100% Orifice Dia.= 22.78 in.

Vent.	7.000	5.000	2.500	1.750	1.250	.750
Tap	2	2	2	2	2	2
Dif.	1.207	.875	.446	.302	.221	.134
	1.205	.880	.433	.303	.221	.135
	1.210	.870	.436	.300	.223	.134
		.875	.432		.221	.135
			.446		.222	
			.443		.224	
Av.	1.2073	.8750	.4393	.3017	.222	.1345
Coeff.	.604	.598	.598	.605	.596	.596



INTAKE ORIFICE COEFFICIENT
.62
.61
.60
.59
.58
• 20% ORIFICE
+ 30% "
△ 45% "
◓ 65% "
□ 65% " (ROUGH)
○ 100% "
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4 in. H_2O
DIFFERENTIAL



COMPARISON WITH LARGE
PIPE ORIFICE COEFFICIENTS
.62
.61
.60
.59
.58
A
B
C
A - Spitzglass 12" Pipe Tap at V. C.
B - Bailey 15" Pipe Tap at V. C.
C - Bureau of Standards 24" Pipe Tap 1/4 Dia.
(Corrected for approach Velocity)
0
20
40
60
80
100%
ORIFICE AREA / PIPE AREA

PLOTTED AGAINST ORIFICE SIZE IN PER CENT PIPE DIAMETER, AS SHOWN BY THE DOTTED LINE ON THE LOWER HALF OF PAGE 40. HERE THERE APPEARS TO BE A SLIGHT INCREASE OF THE COEFFICIENT AS THE ORIFICE SIZE BECOMES SMALLER. IN DRAWING THE LINE, LESS EMPHASIS WAS GIVEN TO THE LAST POINT ON THE LEFT AS ALL THE VENTURIMETER READINGS OF THE 20% ORIFICE WERE LESS THAN .7 INCH OF ALCOHOL, AND IN THIS RANGE ITS CALIBRATION COULD NOT BE SO ACCURATE.

COEFFICIENTS FOR ORIFICES LOCATED WITHIN LARGE PIPES OBTAINED BY SPITZGLASS, BAILEY, AND BUCKINGHAM (THE LATTER OF THE BUREAU OF STANDARDS) WERE PLOTTED WITH THIS LAST CURVE FOR COMPARISON. THE COEFFICIENTS AS ORIGINALLY GIVEN BY THE BUREAU OF STANDARDS INCLUDED THE APPROACH VELOCITY FACTOR, SO THEY WERE DIVIDED BY $\sqrt{\frac{1}{1-\left(\frac{\text{Orifice Area}}{\text{Pipe Area}}\right)^2}}$ TO PLACE THEM ON THE SAME BASIS AS THE OTHERS. THE VALUES OBTAINED IN THIS TEST AGREE WITHIN 1% OF THE AVERAGE OF THE OTHER THREE CURVES.

THE AVERAGE COEFFICIENT FOUND FOR THE INTAKE PIPE ORIFICE, .601, AGREES VERY WELL WITH THOSE FOUND FOR DISCHARGING AIR THROUGH AN ORIFICE FROM A TANK WHOSE CROSS SECTION AREA IS OVER 20 TIMES THAT OF THE ORIFICE ("DURLEY BOX" TYPE). DURLEY'S COEFFICIENTS FOR ORIFICES 5/16 TO 4 INCHES IN DIAMETER CONVERGE ON .60 AS THE DIFFERENTIAL APPROACHES ZERO, WHILE POLSON'S COEFFICIENTS FOR $\frac{1}{2}$ TO $2\frac{1}{2}$ INCH ORIFICES GROUP AROUND .60 WHEN THE HEAD IS LESS THAN 6 INCHES OF WATER. MULLER FOUND THE AVERAGE COEFFICIENT OF THIS TYPE OF ORIFICE TO BE .597 FOR SIZES FROM .92 TO 2.47 INCHES, IRRESPECTIVE OF DIFFERENTIAL.

Watson and Schofield found coefficients to fall within 1% of .596 for all differentials when flow is reversed through the above type of orifice, using openings from $\frac{1}{2}$ to 2 inches in diameter. Ware found that the pressure differential for reverse flow through the Durley Box Orifice was the same for the same rate of flow, within 1%, which further ties in Durley's mean coefficient of .60 with the results of this experiment.

V. CONCLUSION

1. THE INTAKE ORIFICE IS A PRACTICAL DEVICE FOR MEASURING AIR FLOW.

2. A COEFFICIENT OF .601 MAY BE USED FOR ORIFICE SIZES FROM 20% TO 100% AND FOR DIFFERENTIALS FROM. .51 TO 2.3 INCHES OF WATER DIFFERENTIAL.

3. THE OPEN END OF A PIPE MAY BE USED AS AN ORIFICE, ALTHOUGH THE READINGS ARE RATHER UNSTABLE.

4. FLOW THROUGH AN ORIFICE MAY BE MEASURED WITHIN ABOUT 1% ERROR WITHOUT ELABORATE EQUIPMENT, WHEN PRESSURE DIFFERENTIALS ARE AS LOW AS .05 INCHES OF WATER. THIS MAKES THE ORIFICE USE-RUL FOR TESTING OF PROPELLER TYPE FANS AND FOR HEATING AND VENTILATING WORK WHERE ONLY SLIGHT LOSS OF HEAD CAN BE TOLERATED.

5. IN LARGE SIZES, THE IRREGULARITY OR ROUGHNESS OF THE THIN PLATE ORIFICE HAS NO APPRECIABLE EFFECT ON THE COEFFICIENT.

6. THE LOCATION OF VENA CONTRACTA SHIFTS WITH PRESSURE DIFFERENTIAL, ESPECIALLY BELOW ONE INCH OF WATER DIFFERENTIAL. IT, OF COURSE, ALSO SHIFTS WITH THE PER CENT AREA OF THE ORI-FICE, AS HAS LONG BEEN KNOWN IN THE CASE OF THE PIPE ORIFICE.

7. A TAP LOCATED 40% OF THE PIPE DIAMETER DOWNSTREAM MAY BE USED WITHIN ½% ERROR FOR ORIFICE SIZES FROM 20% TO 80% AND FOR PRESSURE DIFFERENTIALS FROM .1 TO 2 INCHES OF WATER.

8. IT IS BELIEVED THAT THE ACCURACY OF THE COEFFICIENT FOUND IN THIS TEST IS WITHIN 1% ERROR.

9. ALTHOUGH THESE TESTS WERE LIMITED TO A 22.75 INCH PIPE AND ORIFICE SIZES ABOVE 10.18 INCHES, IT IS BELIEVED THAT THE LOCATION OF PRESSURE TAPS GIVEN IN TERMS OF PIPE DIAMETER WILL HOLD FOR SMALLER PIPES AS WELL.

THIS IS BECAUSE THE GEOMETRIC SYMMETRY OF THE VENA CONTRACTA FOR PIPE ORIFICES HAS BEEN ESTABLISHED BY SPITZ-GLASS, JUDD, AND OTHERS, AND NO REASON IS KNOWN WHY IT SHOULD NOT BE TRUE IN THE CASE OF THE INTAKE PIPE ORIFICE.

IT IS ALSO BELIEVED THAT THE COEFFICIENT FOUND WILL BE ESSENTIALLY THE SAME FOR GEOMETRICALLY SIMILAR ORIFICES OF SIZES DOWN TO ABOUT 1/4 INCH, SINCE THE VALUE FOUND CHECKS SO WELL WITH THOSE FOUND FOR SMALL ORIFICES DISCUSSED IN PART IV. B.

APPENDIX

A. Calibration of Manometers

The type of micro manometers used is essentially a primary instrument as no corrections or calibrations must be made other than to know the density of the manometer fluid at the temperature used.

In brief, it consists of a horizontal bottle half filled with alcohol used as a reservoir and connected below the fluid level by a flexible hose to a glass tube with a cross hair engraved on it. (See page 10). This inclined tube may be raised or lowered by turning the dial on top of the main screw. The inclination of the tube may be varied to change the sensitiveness of the instrument. For pressures in the neighborhood of .1 inch, and angle of 2° was used giving about .028 inch movement of the meniscus for .001 inch vertical motion, which is easily discernable. The zero may be set by raising or lowering the inclined tube relative to the carriage until the bottom of the meniscus is on the cross hair, having first set the dial on zero.

If the differential of two pressures is to be measured, the lower pressure is connected to the top of the inclined tube and the higher pressure to the reservoir. If one pressure above atmospheric is being measured the connection is made to the reservoir, the top of the cross hair tube being open to the air. For a pressure below that of the air, this connection is shifted to the inclined tube.

IN EITHER CASE, TO MEASURE THE PRESSURE THE DIAL IS TURNED TO RAISE THE INCLINED TUBE UNTIL THE MENISCUS OF THE LIQUID LEVEL IS OPPOSITE THE CROSS HAIR. SINCE THE MAIN SCREW HAS 10 THREADS TO THE INCH, ON REVOLUTION MEANS .1 INCH WHICH IS INDICATED ON THE MAIN COLUMN. THE RIM OF THE DIAL HAS 100 EQUAL DIVISIONS SO THAT .01 REVOLUTION MEANS .001 INCH VERTICAL TRAVEL OF THE CARRIAGE.

ALTHOUGH THIS INSTRUMENT READS DIRECTLY TO .001 INCH OF ALCOHOL AMD MAY BE EASILY ESTIMATED TO .0005 INCHES, ITS ACCURACY IS DETERMINED ENTIRELY BY THE PRECISION WITH WHICH THE MAIN SCREW THREAD IS CUT. THESE SCREWS WERE CUT ON A SPECIAL TOOLMAKER'S LATHE BY AN EXPERT MACHINIST, AND CARE WAS TAKEN WHILE TURNING TO PREVENT HEATING ABOVE THE APPROXIMATE ROOM TEMPERATURE AT WHICH THEY WERE TO BE USED. THE TEMPERATURE CHANGES ENCOUNTERED, HOWEVER, HAVE NO APPRECIABLE EFFECT ON ITS ACCURACY, AS A 20° F. CHANGE IN TEMPERATURE AFFECTS THE LENGTH OF THE BRASS SCREW ONLY .02%.

THE PITCH OF THE SCREWS OF EACH MANOMETER WAS CHECKED WITH A NEW MICROMETER FOR THE ENTIRE 8 INCH LENGTH AND AT NO POINT WAS THERE AN ERROR OF OVER .0005 INCH. THIS IS THE LIMIT OF ACCURACY OF THE EXTENSION TYPE MICROMETER USED.

A GREAT ADVANTAGE OF THIS INSTRUMENT OVER THE USUAL INCLINED MANOMETER IS THAT THE LIQUID LEVEL IN THE RESERVOIR IS UNCHANGED REGARDLESS OF THE READING, SINCE THE SAME VOLUME OF LIQUID IS IN THE TUBE WHATEVER THE READING, SO LONG AS THE MENISCUS IS AT THE CROSS HAIR.

ANOTHER ADVANTAGE IS THAT THERE CAN BE NO ERROR OF UNEVEN CAPILLARY EFFECT IN A TUBE OF VARYING BORE, SINCE FOR ALL READINGS THE LIQUID IS AT THE SAME POSITION IN THE TUBE. WHEN THE INSTRUMENT IS SET ON ZERO, COMPENSATION IS AUTOMATICALLY MADE FOR ANY CAPILLARY RISE OF THE LIQUID. THIS, HOWEVER, IS SMALL, AS A TUBE OF LARGE BORE WAS PURPOSELY USED.

THE DENSITY OF THE ETHYL ALCOHOL USED WAS FOUND BY TWO METHODS: (A) USING A STANDARD HYDROMETER AT 86° F THE SPECIFIC GRAVITY WAS FOUND TO BE .802. (B) BY DRAWING THE LIQUID UP A LONG VERTICAL TUBE CONNECTED TO A SIMILAR TUBE CONTAINING DISTILLED WATER, THE SPECIFIC GRAVITY WAS OBTAINED BY DIVIDING THE HEIGHT OF THE WATER COLUMN BY THE HEIGHT OF THE ALCOHOL COLUMN AND MULTIPLYING THE RESULT BY THE SPECIFIC GRAVITY OF WATER AT THAT TEMPERATURE. IT WAS FOUND TO BE .806 AT 77° F IN THIS CASE, AND BY REFERRING TO THE CURVE ON PAGE 57 IT WILL BE SEEN THAT BOTH DETERMINATIONS FALL ON THE SAME TEMPERATURE-DENSITY LINE.

DISTILLED WATER WAS FIRST TRIED IN THESE MANOMETERS, BUT IT WAS FOUND THAT ITS MENISCUS BROKE WHEN THE TUBE WAS INCLINED AT SLIGHT ANGLES, AND SO ALCOHOL WAS RESORTED TO. ALCOHOL HAS THE ADDITIONAL ADVANTAGE OF GIVING ABOUT 25% GREATER READING FOR THE SAME PRESSURE.

B. Calibration of Pitot Tubes

A properly designed pitot tube needs no calibration as it is merely a device for transmitting to a measuring device the static and total pressures existing in a moving fluid. However, false pressures will be given by a tube which disturbs the flow of the fluid too much.

As told in the discussion of instruments, the tubes used were carefully designed to conform with pitot tubes tested and proved to give correct pressures, and hence no calibration is necessary. To eliminate any possibility of doubt, both tubes were placed in a wind tunnel at the Georgia School of Technology and simultaneous readings were taken at ten different velocities up to 75 miles per hour. There was a constant difference in the differential pressures shown of about 1.3% which would give an error of about .65% difference in the velocity indicated. However, at least part of this error was due to the fact that both tubes were not in the same line of flow and the velocity across the tunnel was not consistent. The relative positions of the two tubes were then reversed and readings in this case showed a fairly constant difference in differential pressure now showing the lower pressure. Hence, by conceling this factor, the net error is $\frac{1.3+(-.7)}{2} = .3\%$, equivalent to .15% error in velocities computed from their readings, which is negligible.

This is not an absolute test, of course, but since each tube was made to different approved standards and checked this close, it may be assumed that both tubes give readings correct enough for all practical purposes.

C. CALIBRATION OF THE VENTURIMETER

AT THE OUTSET, IT WAS DOUBTED THAT THE VENTURIMETER WOULD HAVE A NORMAL COEFFICIENT OF DISCHARGE, BUT IT WAS USED SINCE IT WAS THE ONLY ONE AVAILABLE. IF AN INSTRUMENT IS ACCURATELY CALIBRATED, IT IS IMMATERIAL WHAT ITS COEFFICIENT HAPPENS TO BE.

THE VENTURIMETER WAS CONSTRUCTED OF 20 GAGE GALVANIZED IRON, AND UNFORTUNATELY ITS REDUCING SECTION WAS STRAIGHT, FORMING CORNERS AT ITS INTERSECTION WITH BOTH THE APPROACH SECTION AND THE PRESSURE RECOVERY SECTION. THIS WOULD TEND TO CAUSE DISTURBANCE IN THE FLOW, AND MEANS THAT THE THROAT TAPS HAD TO BE LOCATED ON A RIDGE INSTEAD OF BEING IN A STRAIGHT UNIFORM SECTION AS THEY SHOULD.

ORIGINALLY THERE WERE FOUR ONE INCH HOLES CONNECTED BY A PIEZOMETER RING AT THE THROAT AND THE SAME AT THE APPROACH SECTION TO MEASURE THE STATIC PRESSURE IN THESE PLANES. THESE HOLES WERE SOLDERED OVER AND IN THEIR PLACE EIGHT ONE-EIGHTH INCH HOLES WERE DRILLED AT EACH SECTION AND SLIGHTLY BEVELED TO REMOVE BURRS. LARGE HOLES GIVE FALSE READINGS BY DISTURBING THE FLOW AND BY SETTING UP CURRENTS WITHIN THE PIEZOMETER RINGS.

A WOOD FRAME WAS BUILT ABOUT THE PIPE TO SUPPORT VERTICAL AND HORIZONTAL GUIDES FOR THE PITOT TUBE TRAVERSES. ONE TRAVERSE SECTION WAS 3 FEET 4 INCHES UPSTREAM FROM THE VENTURIMETER REDUCER AND THE OTHER 6.4 INCHES DOWNSTREAM FROM THE STATIC HOLES IN THE THROAT OF THE VENTURIMETER.

THE LATTER LOCATION IS IN THE DIVERGING PIPE FOLLOWING THE VENTURIMETER THROAT WHICH INCREASES ABOUT 1/10 INCH IN DIAMETER FOR EACH INCH OF LENGTH. THE SHORT NOSED PITOT

TUBE WAS USED SO THAT THE IMPACT AND STATIC HOLES WOULD BE NEARER THE SAME PLANE. THE AREA OF THE PIPE AT THE STATIC HOLES WAS USED IN COMPUTING THE FLOW, SINCE THE IMPACT OPENING OF THE PITOT TUBE GIVES THE TOTAL PRESSURE, WHICH IS THE SAME IN DIFFERENT SECTIONS OF A STEADY FLOWING FLUID EXCEPT FOR THE FRICTION LOSS. IN THIS CASE THE FRICTION LOSS IS NEGLIBIBLE, SINCE THE DISTANCE CONSIDERED IS ONLY THE 1 5/16 INCHES BETWEEN THE IMPACT AND STATIC HOLES. THIS MEANS THAT, IN EFFECT, BOTH STATIC AND TOTAL PRESSURES WERE MEASURED IN THE PLANE OF THE STATIC HOLES, AND HENCE THIS AREA WAS USED.

IN MAKING THE TRAVERSES, THE CROSS SECTION OF THE PIPE WAS DIVIDED INTO FIVE EQUAL CONCENTRIC CIRCULAR AREAS AND FOUR READINGS WERE TAKEN 90^0 APART IN THE CENTERS OF EACH OF THE FIVE AREAS. THIS GIVES 20 READINGS FOR EACH TRAVERSE. TO FIND THE RATE OF FLOW, THE AVERAGE VELOCITY IS MULTIPLIED BY THE AREA. SINCE THE VELOCITY IS PROPORTIONAL TO THE SQUARE ROOT OF THE VELOCITY HEAD, INSTEAD OF AVERAGING THE PRESSURES, THE SQUARE ROOT OF EACH READING WAS FOUND AND AVERAGED.

THE ACTUAL QUANTITY OF AIR FLOWING, AS FOUND BY THE PITOT TUBE TRAVERSE IS CALCULATED AS FOLLOWS:

$$U = \sqrt{2GH}$$

$$V = AU = A\sqrt{2GH}$$

$$V = A\sqrt{2G}\ \text{AV.}\sqrt{P}\ \sqrt{\frac{SG \times 62.43}{12 \times D}}$$

U = AVERAGE VELOCITY IN THE PIPE, FT./SEC.

H = HEAD OF THE FLUID FLOWING, FT.

G = ACCELERATION OF GRAVITY, FT/SEC./SEC.

V = VOLUME OF AIR FLOWING, CUBIC FT./SEC.

AV. $\sqrt{P}$ = AVERAGE OF SQUARE ROOTS OF VELOCITY PRESSURE IN INCHES OF ALCOHOL.

SG = SPECIFIC GRAVITY OF ALCOHOL.

D = DENSITY OF AIR FLOWING.

SIMILARLY, THE QUANTITY OF AIR AS MEASURED BY THE VENTURIMETER IS EXPRESSED AS FOLLOWS:

$$V = C\,A_V\,\sqrt{2GH}$$

C = OVERALL COEFFICIENT OF DISCHARGE, INCLUDING APPROACH VELOCITY FACTOR.

A_V = AREA OF VENTURIMETER THROAT, SQ. FT.

$$V = CA_V\,\sqrt{2G}\,\sqrt{P_V}\,\sqrt{\frac{SG_V \times 62.43}{12 \times D_V}}$$

USING THE SAME SYMBOLS AS BEFORE WITH THE SUBSCRIPT $_V$ TO DENOTE VENTURIMETER.

$$C = \frac{\text{ACTUAL FLOW}}{\text{THEORETICAL FLOW}}$$

$$C = \frac{\frac{\pi D^2}{4}\sqrt{2G}\;\text{AV}\sqrt{P}\sqrt{\frac{SG \times 62.43}{12 \times D}}}{\frac{\pi D_V^2}{4}\sqrt{2G}\;\sqrt{P_V}\sqrt{\frac{SG \times 62.43}{12 \times D_V}}}$$

BUT $SG = SG_V$ (SAME ALSOHOL, AT SAME TEMP.)

$D = D_V$ (SAME AIR, PRESSURE WITHIN 1%)

CANCELING ALL EQUAL TERMS,

$$C = \frac{D^2 \times \text{AV.}\sqrt{P}}{D^2_V \times \sqrt{P_V}}$$

USING THIS EXPRESSION, THE VALUE OF C WAS DETERMINED BY 21 SEPARATE 20 POINT TRAVERSES AT VARIOUS RATES OF FLOW. NINE

OF THESE TRAVERSES WERE MADE IN THE MAIN DUCT AND TWELVE WERE MADE IN THE NARROW SECTION FOLLOWING TH THROAT. WHEN IT WAS POSSIBLE, SIMULTANEOUS TRAVERSES WERE MADE IN BOTH SECTIONS. AT VERY LOW RATES OF FLOW ONLY THE THROAT TRAVERSE COULD BE USED AS THE VELOCITY IN THE PIPE WAS TOO LOW TO BE MEASURED.

THE VALUES OBTAINED WERE PLOTTED AGAINST THE VENTURIMETER READING IN INCHES OF ALCOHOL. ALL POINTS EXCEPT THREE SHOWED REMARKABLE AGREEMENT, AND A CURVE DRAWN THROUGH THEM WAS USED TO FIND THE COEFFICIENT FOR ANY RATE OF FLOW.

CALIBRATION OF VENTURIMETER

Diameter at Pipe Traverse Section = 22.77 inches

Diameter at Throat Traverse Section = 12.26 inches

(Readings in inches of Alcohol)

Pipe Traverse

Vent.= 6.795
Dry Bulb= 87
Wet Bulb= 63
Bar. = 28.66

Vert.	Horiz.	Horiz.
.29o	.330	.305
.375	.425	.377
.410	.420	.420
.410	.450	.440
.423	.450	.440
.470	.480	.470
.515	.480	.460
.565	.456	.460
.518	.470	.440
.335	.365	.360

Av. of Sq.Roots
Vert= .65405
Horiz.= .65695
Horiz.= .64495
Averaging vertical with average of horizontals:
Coeff.= .88895

Throat Traverse

Vent=6.795
Wet Bulb= 88
Dry Bulb= 59
Bar. = 29.11

Vert.	Horiz.
.5.068	5.217
5.043	5.158
5.012	5.056
4.925	4.986
4.866	4.957
4.964	4.956
5.086	5.065
5.197	5.153
5.311	5.229
5.198	5.364

Av.of Sq.Rts.
Vert.=.22508
Hori.=.22609
Coeff.=.89088

Pipe Traverse

Vent= 5.500
Dry Bulb= 85
Wet Bulb= 68
Bar.= 29.12

Vert.	Horiz.
.263	.270
.325	.345
.342	.370
.345	.370
.355	.375
.380	.365
.387	.365
.387	.363
.367	.349
.288	.295

Av. of Sq. Roots
.58545 .58831
Coeff. = .88873

Throat Traverse

Vent.= 5.500
Dry Bulb= 80
Wet Bulb= 70
Bar. = 29.12

Vert.	Horiz.
4.115	4.240
4.115	4.177
4.080	4.130
4.040	4.065
3.980	4.150
4.010	4.150
4.090	4.115
4.135	4.178
4.155	4.250
4.145	4.240

Av. of.Sq. Roots
2.0213 2.0406
Coeff.= .89115

CALIBRATION OF VENTURIMETER
(Continued)

Pipe Traverse

Vent.= 4.500
Dry Bulb= 81.5
Wet Bulb= 56.6
Bar. = 29.17

Vert.	Horiz.
.255	.238
.287	.295
.295	.300
.303	.325
.310	.310
.307	.297
.322	.287
.307	.282
.273	.280
.215	.239

Av. of Sq. Roots
.53231 .53358
Coeff.=.89224

Throat Traverse

Vent.=4.00
Dry Bulb=82
Wet Bulb=59
Bar.=29.29
V

Vert.	Horiz.
2.965	3.090
2.960	3.050
2.960	3.005
2.920	2.965
2.895	2.915
2.925	2.920
2.980	2.965
3.025	3.035
3.050	3.070
3.040	3.150

Av. of Sq. Roots
1.7237 1.7363
Coeff.=.89049

Pipe Traverse

Vent.=4.00
Dry Bulb=82
Wet Bulb=59
Bar. =29.29

Vert.	Horiz.
.230	.225
.270	.275
.300	.300
.305	.300
.295	.300
.260	.265
.250	.260
.240	.247
.230	.240
.190	.200

Av. of Sq.Roots
.5079 .5076
Coeff.=.9016

Pipe Traverse

Vent.=3.600
Dry Bulb=82
Wet Bulb=55
Bar.= 29.19

Vert.	Horiz.
.170	.175
.225	..237
.230	.255
.247	.255
.241	.250
.240	.230
.235	.223
.233	.217
.215	.210
.167	.168

Av. of Sq.Roots
.46800 .47013
Coeff.= .8781

Throat Traverse

Vent.=3.25
Dry Bulb=88
Wet Bulb=60
Bar. =29.00

Vert.	Horiz.
2.460	2.500
2.430	2.480
2.410	2.445
2.390	2.405
2.360	2.380
2.385	2.365
2.425	2.410
2.475	2.445
2.465	2.480
2.475	2.510

Av.of Sq.Roots
1.5583 1.5626
Coeff.=.89094

Pipe Traverse

Vent.=3.40
Dry Bulb=83
Wet Bulb=58
Bar. =29.17

Vert.	Horiz.
.162	.174
.205	.228
.225	.247
.237	.247
.235	.240
.235	.220
.215	.215
.220	.208
.220	.208
.165	.170

Av.of Sq.Roots
.45948 .46358
Coeff.=.88891

CALIBRATION OF VENTURIMETER
(Continued)

Pipe Traverse
Vent.=3.25
Dry Bulb=88
Wet Bulb=60
Bar.= 29.00

Vert.	Horiz.
.160	.190
.200	.230
.210	.250
.220	.250
.220	.240
.235	.210
.235	.205
.230	.195
.210	.180
.175	.155

Av.of Sq.Roots
.4572 .4579
Coeff.=.90136

Throat Traverse
Vent.=2.5
Dry Bulb=86
Wet Bulb=68
Bar.= 29.04

Vert.	Horiz.
1.885	1.910
1.880	1.900
1.885	1.870
1.835	1.850
1.813	1.825
1.825	1.825
1.865	1.860
1.893	1.890
1.905	1.910
1.900	1.930

Av.of Sq.Roots
1.3658 1.3683
Coeff.=.8901

Pipe Traverse
Vent.=2.5
Dry Bulb=86
Wet Bulb=68
Bar.=29.04

Vert.	Horiz.
.122	.135
.152	.165
.158	.180
.166	.184
.168	.180
.1750	.164
.1740	.155
.175	.148
.164	.140
.130	.121

Av.of Sq.Roots
.39743 .39579
Coeff.=.8909

Pipe Traverse
Vent.=2.000
Dry Bulb=86
Wet Bulb=68
Bar.=29.04

Vert.	Horiz.
.103	.095
.130	.122
.140	.128
.145	.133
.149	.135
.130	.141
.125	.144
.125	.134
.116	.128
.098	.096

Av.Sq.Roots
.35447 .35371
Coeff.=.8892

Throat Traverse
Vent.=2.000
Dry Bulb=86
Wet Bulb=68
Bar.=29.04

Vert.	Horiz.
1.513	1.535
1.505	1.522
1.483	1.500
1.470	1.482
1.448	1.460
1.460	1.465
1.490	1.495
1.505	1.518
1.512	1.528
1.518	1.540

Av.of Sq.Roots
1.2214 1.2278
Coeff.=.89141

Throat Traverse
Vent.=1.5
Dry Bulb=86
Wet Bulb=68
Bar.=29.04

Vert.	Horiz.
1.137	1.160
1.135	1.145
1.128	1.133
1.115	1.115
1.095	1.097
1.096	1.103
1.114	1.129
1.133	1.140
1.143	1.158
1.135	1.170

Av.of Sq.Roots
1.0597 1.0653
Coeff.=.8931

CALIBRATION OF VENTURIMETER
(Continued)

Throat Traverse

Vent.=1.000
Dry Bulb=86
Wet Bulb=68
Bar.-29.04

Vert.	Horiz.
.770	.770
.760	.766
.750	.750
.742	.743
.735	.735
.742	.735
.750	.753
.762	.763
.765	.775
.765	.780

Av.of Sq.Roots
.8689 .8704
Coeff.= .8955

Throat Traverse

Vent.=0.75
Dry Bulb=90
Wet Bulb=69
Bar.=29.01

Vert.	Horiz.
.580	.585
.570	.575
.568	.570
.563	.560
.555	.555
.558	.560
.567	.570
.575	.575
.578	.585
.578	.593

Av.of Sq.Roots
.7547 .7569
Coeff.=.8982

Throat Traverse

Vent.-.500
Dry Bulb=90
Wet Bulb=69
Bar.=29.01

Vert.	Horiz.
.390	.391
.385	.385
.384	.382
.377	.377
.373	.372
.372	.374
.379	.383
.383	.380
.386	.395
.385	.400

Av.of Sq.Roots
.61766 .61968
Coeff.=.9002

Throat Traverse

Vent.=.250
Dry Bulb=90
Wet Bulb=69
Bar.=29.01

Vert.	Horiz.
.194	.198
.195	.195
.193	.192
.190	.189
.188	.188
.190	.192
.194	.196
.197	.199
.197	.202
.197	.199

Av.of Sq.Roots
.44004 .44180
Coeff.=.90784

Throat Traverse

Vent.=.130
Dry Bulb=78
Wet Bulb=57
Bar.=29.12

Vert.	Horiz.
.103	.103
.103	.102
.102	.100
.102	.099
.100	.098
.101	.100
.102	.102
.102	.104
.103	.103
.103	.098

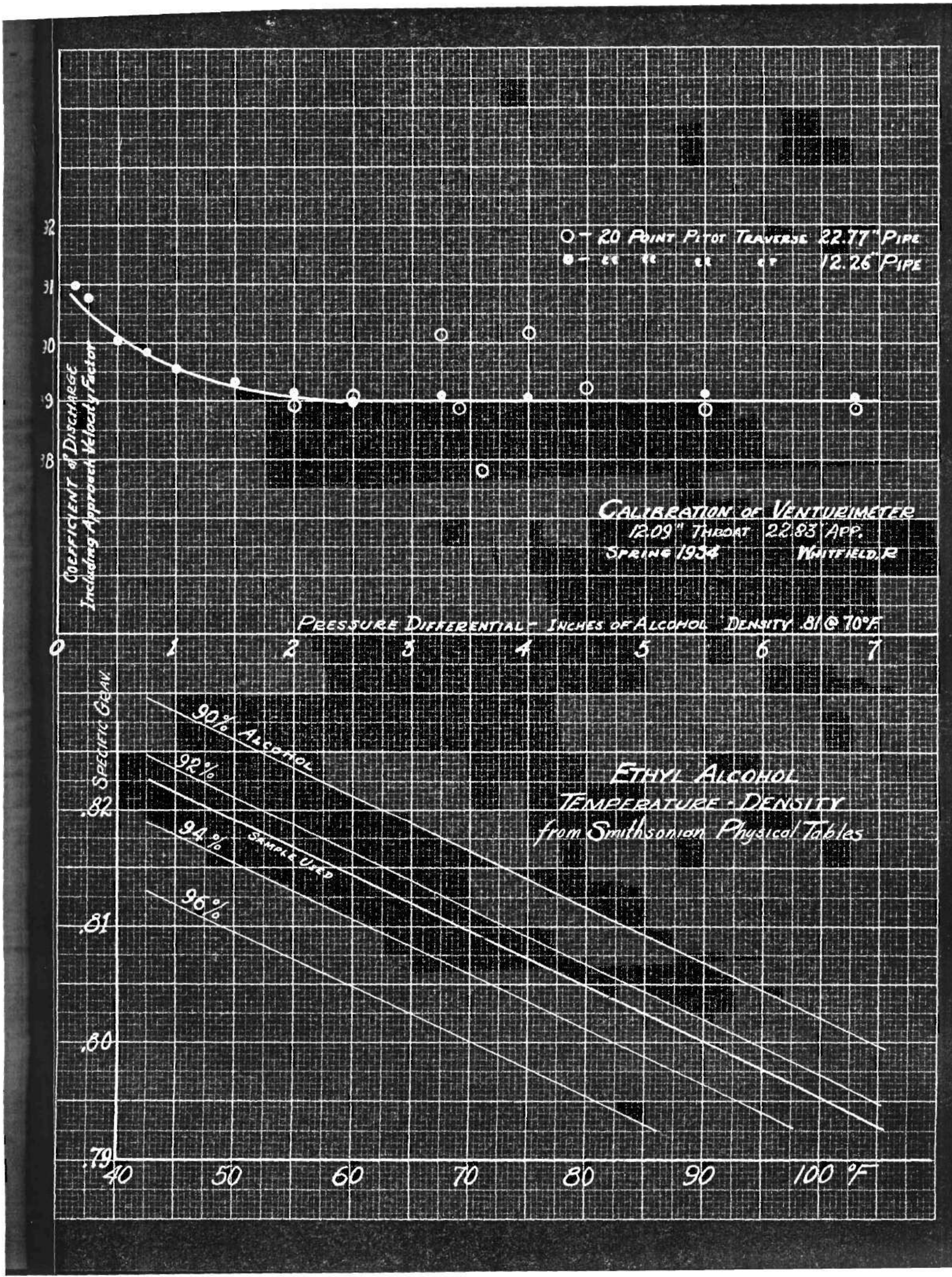
Av.of Sq.Roots
.31958 .31760
Coeff.=.9098

Throat Traverse

Vent.=6.795
Dry Bulb=88
Wet Bulb=59
Bar.=29.10

Vert.	Horiz.
5.068	5.217
5.043	5.158
5.o12	5.056
4.925	4.986
4.866	4.957
4.964	4.956
5.086	5.065
5.197	5.153
5.311	5.229
5.198	5.364

Av.of Sq.Roots
.22508 .22609
Coeff.=.89088



○ – 20 Point Pitot Traverse 22.77" Pipe
● – " " " " 12.26" Pipe
Coefficient of Discharge Including Approach Velocity Factor
Calibration of Venturimeter
12.09" Throat 22.83" App.
Spring 1934 Whitfield, R
Pressure Differential – Inches of Alcohol Density .81 @ 70°F.
0 1 2 3 4 5 6 7
Specific Grav.
90% Alcohol
92%
94% Sample Used
96%
Ethyl Alcohol
Temperature - Density
from Smithsonian Physical Tables
.82
.81
.80
.79
40 50 60 70 80 90 100 °F

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